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NASA CP 10120

THIRD LDEF POST-RETRIEVAL SYMPOSIUM ABSTRACTS

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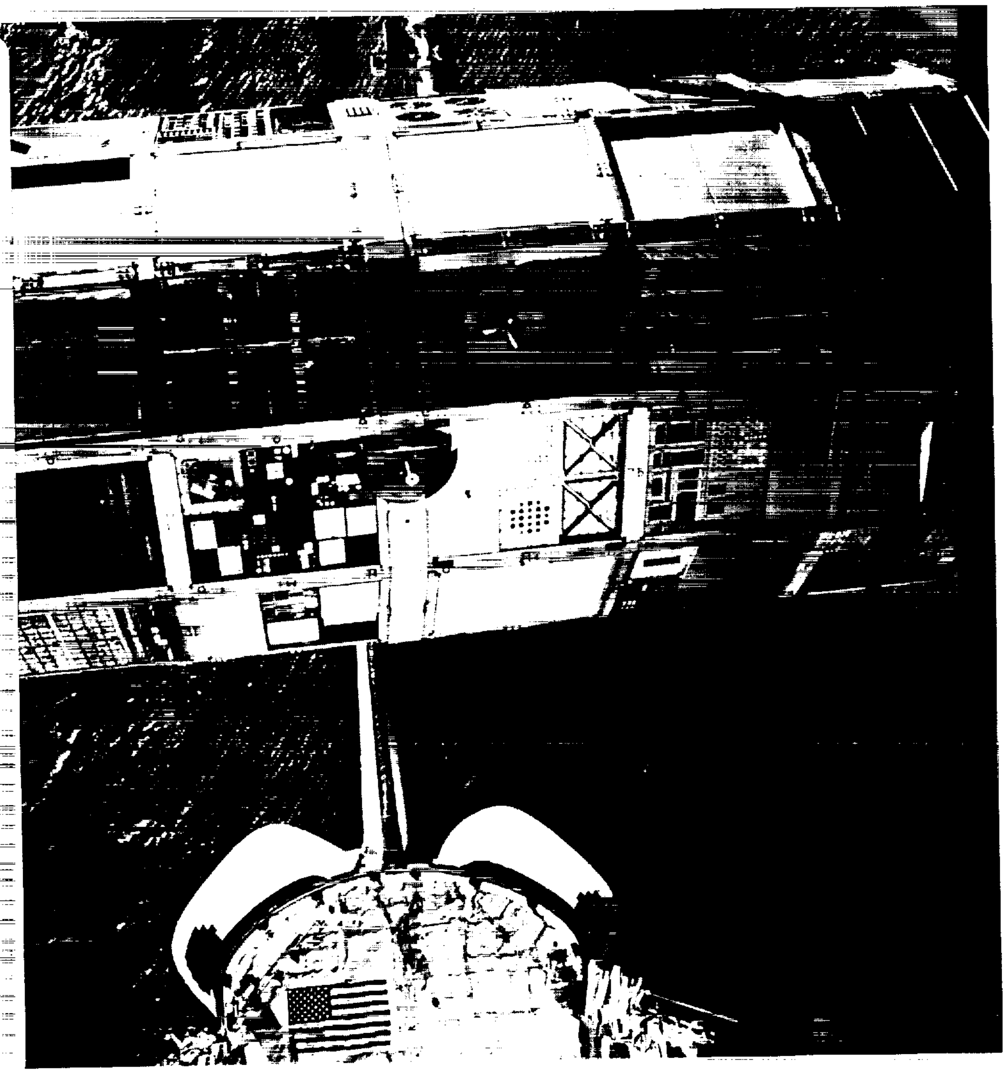

November 8-12, 1993 • Williamsburg Lodge • Williamsburg, Virginia 23185

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Third Post - Retrieval Symposium

Compiled by
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Abstracts of a symposium sponsored by the National Aeronautics and Space Administration, Washington, D.C., and the American Institute of Aeronautics and Astronautics, Washington, D.C., and held in Williamsburg, Virginia
November 8-12, 1993

NASA CP 10120

Foreword

The Long Duration Exposure Facility (LDEF) Science Office at NASA Langley Research Center and the American Institute of Aeronautics and Astronautics will cosponsor the Third LDEF Post-Retrieval Symposium in Williamsburg, Virginia, from November 8 - 12, 1993. The Third Symposium marks a departure from the two previous LDEF Symposia, as the scope of this symposium is expanded to include other space environments and effects experiments, such EURECA, EOIM-3, and Salyut-7 in addition to LDEF results.

In order to build "cheaper-faster-better spacecraft" it is important to understand the space environment and its effects on spacecraft materials, systems, and the living systems that may inhabit the spacecraft. This volume is a compilation of investigator prepared abstracts of LDEF data analysis, as well as results from EURECA, EOIM-3, and Salyut-7 analysis. The Third Symposium and this compilation of abstracts also contain papers on future directions in space exposure experiments, as well as the need for unified programs on space environments and long duration exposure in space. This would enable the data users to have quick and easy access to the critically needed information.

As with the First and Second Symposia, the abstract books for the Third Symposium will be distributed at the conference and the full-length papers will be published as a NASA Conference Publication at a later date. The First Post-Retrieval Symposium was held in Kissimmee, Florida in 1991. The Conference Publication is NASA CP-3134. The Second Symposium was held in San Diego, California in 1992. The Conference Publication is NASA CP-3194. For further information about either of these publications or about the third publication, please contact me:

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LDEF ENVIRONMENT MODELING UPDATES

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ABSTRACT

An updated gas dynamics model for gas interactions around the LDEF is presented that includes improved scattering algorithms. The primary improvement is more accurate predictions of surface fluxes in the wake region. The code used is the Integrated Spacecraft Environments Model (ISEM).

Additionally, initial results of a detailed ISEM prediction model of the Solar Array Passive LDEF Experiment (SAMPLE), A0171, is presented. This model includes details of the A0171 geometry and outgassing characteristics of the many surfaces on the experiment. The detailed model includes the multiple scattering that exists between the ambient atmosphere, LDEF outgassing and atomic oxygen erosion products. Predictions are made for gas densities, surface fluxes and deposition at three different time periods of the LDEF mission.

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OUTGASSING PRODUCTS FROM ORBITER TILE AND HARDWARE CLEANLINESS CRITERIA

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ABSTRACT

The shuttle orbiters are known to be significant sources of outgassing in low Earth orbit. Infrared spectra of residues from orbiter thermal tiles and mass spectra of outgassing from thermal tiles will be presented. Recommendations to minimize effects of the outgassing on sensitive instrument surfaces will be made. Inadequacy of mass loss cleanliness criteria for selection of material and processing of flight hardware for contamination-sensitive instruments will be discussed. Material selection for flight hardware is usually based on mass loss (ASTM E-525). However, flight hardware cleanliness criteria (MIL 1246A) is a surface cleanliness assessment. It is possible for materials (i. e. Sil-Pad 2000) to pass ASTM E-525 and fail MIL 1246A class A by orders of magnitude. Conversely, it is possible for small amounts of non-conforming material (i. e. Huma-Seal conformal coating) to not present significant cleanliness problems to a contamination-sensitive instrument (LITE). Effective cleaning and cleanliness verification are essential for contamination-sensitive flight instruments.

INDUCED PAYLOAD CONTAMINATION AS OBSERVED ON THREE SUCCESSIVE FLIGHTS OF THE SPACE SHUTTLE

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ABSTRACT

Post-flight analysis of three recent shuttle flights suggests a relationship between the contamination found on science payloads manifested on the Orbiter Atlantis (OV-104). Observations by experimenters on STS-44, STS-45 and STS-46 indicated the presence of a contaminant coating on their returned hardware. Two of the most important observations made during the periods of instrument operation were the fact that contamination "return flux" was depositing in the payload bay during attitude changes and that the deposits could not be removed by high temperature bakeout. Attempts were made to remove the deposits by raising the temperature of the surfaces to +80° C. The return flux appears to be associated with species other than thruster species. It has been ascertained that the molecular deposits are organic silicone materials. The "return flux" phenomena was first seen by the STS-3/OSS-1 Contamination Monitor Package. The species in question at that time was also a silicone polymer. Data also confirms the fact that the payload bay of STS-44 was in an extremely clean condition when launched and, as such, did not contaminate the prime payload (deployed within seven hours).

FTIR spectroscopy has suggested that the principal species observed on the hardware is a silicone, possibly a by-product of DMES, RTV-560, or the beta cloth payload bay liner. DMES is the material used for re-waterproofing the shuttle tiles. RTV-560 is the adhesive used to bond the thermal tiles to the structure. It should be noted that prior to each flight ~100 kilograms of DMES re-waterproofing agent is injected into the TPS tiles.

Since the source(s) of this contaminant has not yet been pinpointed, it was determined that, as a minimum, a detailed cleaning program would be established to "wipe" the beta cloth payload bay liner. One of the science instruments that experienced a moderate deposit of the silicone contaminant on STS-45 was re-flown on STS-56. Although a different Orbiter was used, the detailed beta cloth liner cleaning was performed to assess the impact.

An in-depth discussion of the instrument packages flown on the three (3) missions and observed contamination will be presented. The results of the special cleaning, including a comparison of data will be presented for the instrument flown on the STS-45 and STS-56 missions.

EURECA

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EURECA 11 MONTHS IN ORBIT
INITIAL POST-FLIGHT INVESTIGATION RESULTS

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ABSTRACT

The EUropean REtrievable CArrier (EURECA) was deployed by the space shuttle on 3. August 1992 and retrieved on 23. June 1993. It is the largest spacecraft ever built by Europe and the first to be retrieved from space since the recovery of LDEF.

The primary mission objective of EURECA was the investigation of materials and fluids in a very low micro-gravity environment. In addition other experiments were conducted in space science, life science, technology and space environment disciplines.

The orbit of EURECA was nearly circular with an inclination of 28.5° and an initial altitude of about 510 km. While this orbit was similar to LDEF's the attitude was different with EURECA's top face and fixed solar arrays sun-pointing throughout most of the mission.

The opportunity for conducting a post-flight investigation, of the effects of 11 months in a low Earth orbit on EURECA, has been taken by the European Space Agency to ensure the full exploitation of this successful mission. These investigations will add to and complement the knowledge gained from LDEF.

This paper will give an overview of the EURECA spacecraft and mission, discuss some of the flight anomalies experienced and present the plan and initial results of the post-flight investigation of materials and meteoroid/debris impacts.

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SPACECRAFT SURVEYS: LDEF'S M-D SIG AND ESA'S EURECA POST FLIGHT ANALYSIS: FIRST RESULTS COMPARED.

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ABSTRACT

LDEF's Meteoroid and Space Debris Investigator Group (M-D SIG) set the "gold standard" for the analysis and archiving of retrieved spacecraft. The return of ESA's Eureca spacecraft, with 9 months exposure commencing July 1992 offers further opportunity to extend this LDEF's record to a new epoch. ESA's Post Flight Analysis Programme (1) commences with fast automated scanning at high resolution of the entire spacecraft during, but not delaying de-integration procedures. Photographic analysis takes place "downstream" with post-acquisition image analysis software, yielding feature description, entered into a database compatible with NASA's M-D SIG.

First results of the analysis are presented and compared with LDEF's 5.75 year exposure. Questions on the growth of space debris and the constancy of the meteoroid flux will be addressed.

References

(1) Aceti, R., Drolshagen, G., Gerlach, L., Meteoroid and Debris Investigation on Eureca, *Proc. First European space Debris Conf., Darmstadt, Germany, 1993,* in press.
(2) NASA Meteoroid and Debris Special Investigator Group (M-D SIG) LDEF Reports and Database.
(3) McDonnell, J.A.M., Deshpande, S.P., Niblett, D.H., Neish, M.J. and Newman, P.J., The Near Earth Space Impact Environment - An LDEF Overview, submitted to World Space Congress, Washington, 1992.

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EXPERIMENT NO. AO 023

POST FLIGHT ANALYSES OF THE EUROPEAN RETRIEVABLE CARRIER - AN IMPACT DAMAGE ASSESSMENT

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ABSTRACT

A summary is given of the hypervelocity impact damage to the European spacecraft Eureca seen during the post flight optical survey. The techniques employed for the survey are the subject of another paper.

Eureca's exposed surfaces are dominated by the presence of beta cloth clad multilayer insulation (MLI) and a large area of solar array materials, namely solar cell cover glass and carbon fibre reinforced composite with various claddings. Optics, bare structural alloys, painted surfaces and second surface mirror materials are also present to a much lesser extent. Considerable differences thus exist between those surfaces that are to be used for the mass flux measurements on Eureca than those used for LDEF.

Additionally, the attitude regime for Eureca is predominantly sun pointing, thereby complicating a geocentric analysis of directional fluxes. From an engineering standpoint however, a phenomenological damage description is nevertheless valuable, and relevant to all variably pointing, slewing spacecraft.

Effects relating to the induced environment will be analysed taking into account that Eureca is equipped with hot (monomethyl hydrazine) and cold (nitrogen) thrusters and the mission included a brief period of experimental ion thruster operation. Gross combinatorial effects with impact damage are not expected; nor is significant atomic oxygen exacerbated damage likely on millimetre scales as the fluence is much lower, and surfaces well protected.

The main paper will document all major sites found and discuss in depth the surprises that Eureca has in store for hypervelocity impact physicists, space debris analysts, and those concerned with impactor damage experienced by low Earth orbit spacecraft.

POST FLIGHT ANALYSES OF THE EUROPEAN RETRIEVABLE CARRIER - OPTICAL SURVEY TECHNIQUES

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ABSTRACT

The optical examination of the European Retrievable Carrier (Eureca) is described.

Eureca differs from LDEF in several major respects relevant to impact damage studies. These are:

1 Eureca is presently intended for reflight in the near term, and therefore all components remain under configuration control, and no analyses are permissable where additional reflight costs would be likely.

2 Eureca has a very large area of well characterised hypervelocity impact physics target material; namely solar cell cover glass.

3 The spacecraft also has a very large exposed area of beta cloth, an extremely difficult surface to locate and characterise sub millimetre impact phenomena.

4 This same beta cloth is the outer leaf of a very great deal of multilayer insulation; a construction not dissimilar to some intact capture experiment designs.

5 In order to satisfy the needs of those who subscribe to Eureca's primary mission, de-integration is extremely swift, and most outer surface materials are removed in the first four weeks after retrieval.

These characteristics lead to an optical survey having a high priority within the Eureca Post Flight Analysis Programme of the European Space Agency. Priorities within the survey activity are to record numbers and morphologies of impact sites and to identify material for sampling where the surface nature is amenable to laboratory analysis.

This paper describes the instrumentation and techniques used to document the surfaces exposed to the space environment during the 11 month mission. A qualitative comparison between the image database derived from LDEF and the Eureca library is drawn.

A summary of this survey in terms of damage to Eureca are the subject of another paper.

SEARCH FOR BERYLLIUM-7 ON THE EURECA SPACECRAFT

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ABSTRACT

The discovery of the accretion of cosmogenic ^{7}Be on the leading edge surfaces of the Long Duration Exposure Facility (LDEF) was an unexpected result of the induced radioactivity survey of the spacecraft. The inferred density of ^{7}Be at the orbital altitude of the LDEF was three orders of magnitude higher than that expected due to production in situ by cosmic rays and energetic trapped protons (Phillips, *et al.*, 1991). Measurements of radioactivity on spacecraft structural elements and experimental trays removed from the LDEF confirmed that the ^{7}Be was deposited only on the leading edge of the spacecraft. The activity could not be rubbed off, but could be removed with an acid etch of the surface, thus confirming that it was, indeed, a surface effect (Fishman *et al.*, 1991).

The question remains whether ^{7}Be should be added to the list of 'contaminants' encountered by a spacecraft in low-Earth orbit. Was the observed LDEF concentration an anomaly due to the increased solar activity that occurred in the months prior to retrieval? Should ^{7}Be be expected on all spacecraft surfaces? What is the altitude dependence? How does the density vary with altitude and latitude? Further observations are clearly needed.

The return of the EURECA to Earth provides a rare opportunity for an additional observation of the presence of ^{7}Be on spacecraft surfaces. The results of an induced radiation survey of the EURECA spacecraft as well as results from low-background measurements of a stainless steel disk flown on EURECA will be presented. Two high purity germanium detectors were used, one belonging to ISST and one on loan from the British Defence Research Agency (courtesy of Dr. Clive Dyer). Measurements were performed during spacecraft deintegration processing at the Astrotech facility in Titusville, FL.

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Fishman, G. J., Harmon, B. A., Gregory, J. C., Parnell, T. A., Peters, P., Phillips, G. W., King, S. E., August, R. A., Ritter, J. C., Cutchin, J. H., Haskins P. S., McKisson, J. E., Ely, D. W., Weisenberger, A. G., Piercey, R. B., and Dybler,T., "Observation of 7Be on the surface of the LDEF spacecraft", *Nature* Vol 349, 21 Feb, 1991.

Phillips, G. W., King, S. E., August, R. A., Ritter, J. C., Cutchin, J. H., Haskins, P. S., McKisson, J. E., Ely, D. W., Weisenberger, A. G., Piercey, R. B., and Dybler, T., "Discovery of Be-7 Accretion in Low Earth Orbit", AAS 91-076, *Guidance and Control 1991*, Vol. 74, *Advances in the Astronautical Sciences*, 1991.

DOSIMETRIC RESULTS ON LDEF AND EURECA

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ABSTRACT

Passive detector packages were exposed on LDEF at two different locations as part of the Biostack experiment and at several locations around EURECA. The packages consist of different plastic nuclear track detectors, nuclear emulsion and thermoluminescence dosimeters. Evaluation of these detectors yields data on absorbed dose and particle and LET spectra, from which equivalent doses can be calculated.

LDEF was retrieved after 6 years in space, EURECA stayed over 10 months in orbit. Both spacecraft flew at an inclination of 28.5°. The altitude of EURECA remains constant at 506 km during nearly the whole mission time, whereas the altitude of LDEF decayed from 477 km to 334 km at retrieval. Both spacecraft were stabilized. EURECA was flown shortly after a period of maximum solar activity, LDEF mostly during minimum solar activity. The dosimetric data of both missions are valuable and important since both spacecraft stayed close to the prospected orbit of the space station.

This paper will give a summary of the dosimetric data obtained from the Biostack experiment on LDEF and some very preliminary results of dosimeter packages from EURECA. Both data sets will be compared to each other with model predictions.

PRELIMINARY RESULTS OF RADIATION MEASUREMENTS ON EURECA*

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ABSTRACT

The nearly eleven-month duration of the EURECA mission allows long-term radiation effects to be studied similarly to those of the Long Duration Exposure Facility (LDEF). Basic data can be generated for projections to crew doses and electronic and computer reliability on spacecraft missions. A radiation experiment has been designed for EURECA which uses passive integrating detectors to measure average radiation levels. The components include a Trackoscope, which employs fourteen plastic nuclear track detector (PNTD) stacks to measure the angular dependence of high LET (≥6 keV/μm) radiation. Also included are TLDs for total absorbed doses, thermal/resonance neutron detectors (TRNDs) for low energy neutron fluences and a thick PNTD stack for depth dependence measurements. LET spectra are derived from the PNTD measurements. Preliminary results from the experiment will be presented.

*Work partially supported by NASA Grant No. NAG9-235, NASA-Johnson Space Center, Houston, TX

PERFORMANCE CHARACTERIZATION OF EURECA RETROREFLECTORS WITH FLUOROPOLYMER-FILLED SiO_X PROTECTIVE COATINGS

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ABSTRACT

Aluminized corner-cubed polymethylmethacrylate retroreflectors were coated with 92% SiO_X-8% fluoropolymer (by volume) and flown on the EURECA spacecraft. The fluoropolymer-filled SiO_X protective coating was found to be durable to atomic oxygen when exposed in a ground-based plasma asher to an anticipated mission fluence of $2x10^{20}$ atoms/cm^2. Unprotected retroreflector surfaces were found to develop highly diffuse reflectance characteristics, thus inhibiting their use for laser retroreflector purposes. A noncontacting retroreflector optical characterization system was constructed and used to measure the optical retroreflection characteristics of retroreflector material which was uncoated, coated and unexposed, coated and exposed to ground laboratory atomic oxygen, and coated and exposed in space on the EURECA spacecraft. A comparison of the results of the optical characterizations will be presented.

EFFECT OF THE SPACE ENVIRONMENT ON MATERIALS FLOWN ON THE EURECA/TICCE-HVI EXPERIMENT

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ABSTRACT

The primary benefit of accurately quantifying and characterizing the space environmental effects on materials is longer spacecraft life. Knowledge of the limits of materials allows the designer to optimize the spacecraft design so that the required life is achieved. Materials such as radiator coatings that have excellent durability result in the design of smaller radiators than a radiator coated with a lower durability coating. This may reduce the weight of the spacecraft due to a more optimum design. Another benefit of characterizing materials is the quantification of outgassing properties. Spacecraft which have ultraviolet or visible sensor payloads are susceptible to contamination by outgassed volatile materials. Materials with known outgassing characteristics can be restricted in these spacecraft. Finally, good data on material characteristics improves the ability of analytical models to predict material performance.

A flight experiment was conducted on the European Space Agency's European Retrievable Carrier (EuReCa) as part of the Timeband Capture Cell Experiment (TICCE). Our main objective was to gather additional data on the space debris environment, with the focus on understanding growth in Spatial Density as a function of size (mass) for hypervelocity particles 1E-06 cm and larger. In addition to enumerating particle impacts, hypervelocity particles were to be captured and returned intact. Measurements were performed post flight to determine the flux density, diameters, and subsequent effects on various optical, thermal control and structural materials.

In addition to these principal measurements, the experiment also provided a structure and sample holders for the exposure of passive material samples to the space environment, e.g., thermal cycling, and atomic oxygen, etc.

An in depth discussion of the flight experiment will be presented, including the techniques used for intact capture of particles. Effects of cratering and impacts on the various materials will be discussed. Measured changes in the optical properties (BRDF) of mirrors will also be presented.

Ionizing Radiation

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LDEF CONTRIBUTIONS TO COSMIC RAY AND RADIATION ENVIRONMENTS RESEARCH

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ABSTRACT

LDEF-1 carried three experiments which are producing significant advances in our knowledge of ultra heavy and anomalous cosmic rays, solar flare particles, and heavy nuclei in the trapped belts. Nine other experiments made measurements on the radiation environments or performed dosimetric monitoring. Data from those experiments, and from measurements of induced radioactivity in LDEF components, have significantly improved our knowledge of the LEO radiation environment. Measurements at various locations and shielding depths of radiation absorbed dose, linear energy transfer spectra, proton, neutron and heavy ion fluences, and induced radioactivity have been made, and many of these results have been compared to models. This has allowed the assessment of accuracy, and the potential for improvement, of the models. Serendipitous results from the radiation measurements include the discovery of atmospheric ^{7}Be plated on the front surface of LDEF, which has motivated a series of new investigations. A sample of measurements and modeling results will be presented, as well as the status of archiving the measurements and models.

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EVIDENCE FOR THE DETECTION OF TRAPPED IRON NUCLEI ON LDEF

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ABSTRACT

The extra long duration of the LDEF mission made it possible to collect a reasonable number of rare heavy ions in a track detector stack. All detected particles in the energy range 20-200 MeV/nuc have energies well below the geomagnetic cutoff for fully stripped nuclei.

A sufficient number of particles with nuclear charge Z>14 was available to study the angular distribution of the arrival direction and the energy spectra. The main objective of this study was the search for trapped heavy ions collected during the transition of LDEF through the South Atlantic Anomaly. The detected Argon ions below 50 MeV/nuc are consistent with the trapping model of the anomalous cosmic rays (which was confirmed for oxygen ions by track detector experiments on Russian satellites). However, the origin of the detected iron population is not yet clear. Below 50 MeV/nuc the arrival direction and the energy spectrum is consistent with a trapped component at McIlwain-parameter values of L=1.4-1.6. In the energy range 50-200 MeV/nuc the iron particles seem to have access from outside the magnetosphere as partly ionized ions with a constant detected mission averaged flux of (3.3 +- 1.0) 10E-8/(m2 s ster MeV/nuc).

The report will include additional actual results from the continued analysis.

RESULTS FROM THE HIIS EXPERIMENT ON THE IONIC CHARGE STATE OF SOLAR ENERGETIC PARTICLES

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ABSTRACT

Cosmic rays are generally believed to be bare nuclei, fully stripped of all orbital electrons. One of the primary goals of the Heavy Ions in Space (HIIS) experiment is to investigate possible sources of partially-stripped heavy ions. The study of such ions is of astrophysical interest, especially at high energies where the cross-section for electron-stripping greatly exceeds the cross-section for electron pick-up. In this case, a measurement of the mean ionic charge state significantly constrains the amount of matter traversed by the ions, thereby helping to identify their source and the mechanism by which they have been accelerated to high energies. Partially-ionized heavy ions are also of potential practical importance: they are less effectively deflected by the Earth's magnetic field than fully-ionized cosmic rays and may therefore constitute an important component of the ionizing-radiation environment encountered by humans and hardware in low-Earth orbit.

It has long been known that low-energy solar energetic particles (SEPs) are partially-ionized. (For example, for solar energetic Fe ions at ~1 MeV/nucleon, the measured mean ionic charge state is $\langle Q \rangle = 14.9 \pm 0.1$.) Some theoretical models for SEP acceleration suggest that these partially-ionized states should continue to higher energies, but up to now there has been no direct experimental support of this notion. We report here HIIS observations of Fe-group ions at 50-800 MeV/nucleon, at energies and fluences which cannot be explained by fully-ionized galactic cosmic rays. Above ~200 MeV/nucleon, all features of our data -- fluence, energy spectrum, elemental composition, and arrival directions -- can be explained by the large SEP events of October 1989, *provided* that the mean ionic charge state at these high energies is comparable to the measured value at ~1 MeV/nucleon. The source of the ions below ~200 MeV/nucleon is not yet understood. (See Kleis *et al.*, these proceedings.)

At the high energies observed by HIIS, SEPs can penetrate typical amounts of shielding. We also discuss the significance of the HIIS results for estimates of the radiation hazard posed by large SEP events to satellites in low-altitude, low-inclination orbits.

EXPERIMENT NO. M0001

CHARACTERISTICS OF LOW ENERGY IONS OBSERVED IN THE HEAVY IONS IN SPACE (HIIS) EXPERIMENT

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ABSTRACT

We present data on the lowest-energy heavy ions observed in the Heavy Ions in Space (HIIS) experiment, which was mounted on the space-facing end of LDEF. These data come from the Lexan sheets at the top of the HIIS detector stacks. For Fe, the energy range of the observed ions is approximately 30-100 MeV/nucleon, far below the geomagnetic cutoff for fully-ionized cosmic rays in the LDEF orbit, even in the presence of severe cutoff suppression due to geomagnetic storms.

The origin of these low energy ions is not yet understood, but possible sources include partially-ionized solar energetic particles, the anomalous component of cosmic rays, and geomagnetically-trapped heavy ions. We will present preliminary results on the fluence, energy spectrum, elemental composition, and arrival directions of the observed ions. We will compare our observations to results from the A0015 and M0002 experiments [Beaujean *et al.*, these proceedings], which covered comparable energy ranges but were mounted on the sides and Earth-facing end of LDEF. We will also compare to HIIS measurements at higher energies [Tylka *et al.*, these proceedings]. Our data and these comparisons should help to clarify the source or sources of the observed ions.

EXPERIMENT NO. M0001

EARLY RESULTS FROM THE ULTRA HEAVY COSMIC RAY EXPERIMENT

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ABSTRACT

Data extraction and analysis of the LDEF Ultra Heavy Cosmic Ray Experiment is continuing. Almost twice the pre LDEF world sample has been investigated and some details of the charge spectrum in the region from $Z \sim 70$ up to and including the actinides will be presented. The early results indicate r-process enhancement over solar system source abundances.

ABSORBED DOSE, LET SPECTRA AND NEUTRON MEASUREMENTS ON LDEF*

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ABSTRACT

Total absorbed doses measured with TLDs, linear energy transfer (LET) spectra measured with plastic track detectors and low energy neutrons measured on LDEF have been compared with model calculations and accelerator experiments. The total absorbed doses measured in TLDs were higher than predicted by the calculations. LET spectra, measured with plastic nuclear track detectors (PNTDs) also deviate significantly from calculations especially for high LET particles ($LET_{\infty} \cdot H_2O >$ 100keV/μm).

Calibration measurements have been made with accelerator exposures of high energy protons. The increase of high LET particles as a function of shielding depth in an LDEF stack could be explained by a comparison with an accelerator experiment with 160 MeV protons applied to a similar stack flown on LDEF. We also found, in comparison with accelerator experiments, that shape analyses of the LET spectrum may provide information about the directionality of the trapped proton radiation environment of LDEF. We have made measurements of the mission fluence energy spectrum produced by trapped protons of two distinct energies from the west direction and found them to be lower than prerecovery estimates.

Analysis of polycarbonate PNTDs from the West-side of LDEF have revealed a very high fluence of tracks ($>1.7 \times 10^7$ tracks/cm^2 under 2 gm/cm^2 shielding). Fluence drops off rapidly as shielding depth increases. To date no adequate explanation for this observation has been found.

We plan to measure range distribution of very high LET ($LET_{\infty} \cdot H_2O > 500$keV/$\mu$m) secondary particles produced in silicon wafer by high energy primary cosmic ray particles. Refinements of experimental techniques and model calculations are also going on to answer specific questions and to understand existing discrepancies between experimental measurements and calculations.

*Work supported by NASA—Marshall Space Flight Center, Huntsville

FISSION FOIL MEASUREMENTS OF NEUTRON AND PROTON FLUXES IN THE A0015 EXPERIMENT*

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ABSTRACT

The radiation environment of LDEF included fluxes of protons and neutrons in significant quantities extending up to about 100 GeV in energy. The spectra of these particles were dependent on surface position on the LDEF satellite and shielding depth. Detectors using fission foils offer a passive means of measuring fluxes of these particles above a series of threshold energies. The fission cross-sections of ^{238}U, ^{232}Th, ^{209}Bi and ^{181}Ta have thresholds between 1.2 and 600 MeV for neutrons and 18 to 600 MeV for protons.

The A0015 experiment on LDEF was composed of complements of passive radiation detectors in two sealed canisters; at the Earth end and near the trailing edge of LDEF. Each cansiter contained a set of fission foil detectors. The detectors were composed of metallic foils between muscovite mica discs. The mica registers the tracks of fission fragments emitted from the foil surfaces. The detectors are calibrated in units of tracks per incident nucleon as functions of nucleon energy.

The measured track densities are converted to neutron and proton fluences with the aid of calculations based on environmental models and propagation through shielding. The track densities are compared with expectations based on calculated proton and neutron spectra to evaluate the accuracy of the radiation modeling to be evaluated.

*Work supported by NASA—Marshall Space Flight Center, Huntsville

MEASUREMENT OF TRAPPED PROTON FLUENCES IN MAIN STACK OF P0006 EXPERIMENT*

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ABSTRACT

To obtain trapped proton fluences and angular distributions the tracks of stopping light particles were measured with plastic nuclear track detectors (CR-39 with DOP) at two different depths in the main stack of the P0006 experiment on LDEF. The results confirmed that the primary proton fluence is directional and provided a definition of preferred particle direction of arrival. The differential primary proton fluences obtained at two energies were compared with theoretical pre-recovery estimates. The large differences observed emphasize the necessity of further improvements in calculational models.

*Work supported by NASA—Marshall Space Flight Center, Huntsville

CHARGE, ENERGY AND LET SPECTRA OF HIGH LET PRIMARY AND SECONDARY PARTICLES IN CR-39 PLASTIC NUCLEAR TRACK DETECTORS OF THE P0006 EXPERIMENT*

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ABSTRACT

We have measured the charge, energy and linear energy transfer (LET) spectra of about 800 high LET ($LET_{\infty} \cdot H_2O > 50 keV/\mu m$) particles in CR-39 plastic nuclear track detectors in the P0006 experiment of LDEF. Primary particles with residual range at the reference surface greater than about 2 microns and secondary particles produced in the detector material with total range greater than about 4 microns were measured. We have used a multi-etch technique and an internal calibration to identify and measure the energy of the particles at the reference surface. The LET spectrum was obtained from the charge and energy distribution of the particles.

*Work supported by NASA—Marshall Space Flight Center, Huntsville

DEPTH DEPENDENT TRACK DENSITY AND LET SPECTRUM MEASUREMENTS WITH PLASTIC NUCLEAR TRACK DETECTORS IN THE A0015 EXPERIMENT*

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Total track densities in CR-39 plastic nuclear track detectors were counted in the A0015 West-side stack at five shielding depths. Track density was seen to increase as a function of shielding depth. LET spectra were measured at two shielding depths. The increase in the density of high LET particles as a function of shielding depth can be explained by a comparison with an accelerator exposure of 160 MeV protons in a similar CR-39 stack.

*Work supported by NASA—Marshall Space Flight Center, Huntsville

LET MEASUREMENT OF HZE PARTICLES IN PLASTIC NUCLEAR TRACK DETECTORS AND TRACING OF PARTICLE TRAJECTORIES INTO *ZEA MAYS* SEEDS IN THE A0015 FREE FLYER BIOSTACK*

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SUMMARY

Zea mays (corn) seeds were exposed to the space radiation environment as part of the A0015 Free Flyer Biostack experiment on LDEF. Layers of CR-39 and Lexan plastic nuclear track detector (PNTD) were placed above and below the monolayers of corn seeds to record the passage of HZE particles through the seed layers. Measurement of LET and tracing of particle trajectories through the PNTD layers and into individual seeds is underway. To date most of the flight and control seeds have been planted and the leaves of some plants show unusual yellow stripes indicative of radiation induced mutations. Following PNTD analysis, an attempt will be made to correlate particle trajectories measured in PNTDs and projected into target seeds with specific radiation induced mutations observed in developing plants.

*Work supported by NASA—Marshall Space Flight Center, Huntsville

PREDICTIONS OF LET SPECTRA MEASURED ON LDEF

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ABSTRACT

Calculational models for predicting linear energy transfer (LET) spectra and associated radiation effects (e.g., electronics upsets, biological damage, sensor noise) related to spacecraft and mission design assessments commonly consider shielding effects and LET contributions only for the primary particles in the space radiation environment. LET spectra measured on LDEF by plastic nuclear track detectors (PNTDs) indicate the presence of a high-LET component that is apparently due to elastic recoil ions and non-elastic collision products produced by the high flux levels of trapped protons in the South Atlantic anomaly region. To investigate the LET production mechanisms and to obtain model comparisons with the LDEF observed spectra, a two-step calculational method has been developed in which analytical radiation transport methods are used in conjunction with environment models and a 3-D spacecraft mass/geometry model to obtain directional proton and cosmic ray spectra within the dosimetry package, and this is then used as the radiation source for a 3-D Monte Carlo transport calculation within the dosimeter. The Monte Carlo calculation takes into account proton induced secondary particle production and transport by using a modified version of the HETC code. Predictions using this calculational method are compared with LET spectra measured on LDEF.

[1] Work supported by NASA Marshall Space Flight Center, Huntsville, Alabama.

DOING PHOTONS WITH MERLIN II AT OROVILLE

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ABSTRACT

A very large n-type high-purity Ge-semiconductor detector has recently been installed at the Lawrence Berkeley Laboratory's underground low-background facility at Oroville. This detector, MERLIN II, has a rated "efficiency" nearly 4 times higher than our original MERLIN detector, which was used extensively to analyse samples from the LDEF satellite. We present results from MERLIN II analysis on some of the same LDEF samples, to provide direct evidence for the improvement in performance achieved with the larger detector. Comparisons are also made between the actual MERLIN II performance and predictions presented at the Second LDEF Post-Retrieval Symposium in June 1992.

Status of LDEF Activation Measurements
and Archive

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We review the status of induced radioactivity measurements for the LDEF spacecraft which includes studies of the nuclide, target, directional and depth dependences of the activation. Analysis of the data has focused on extraction of the specific activities for many materials to develop a global picture of the low earth orbital environment to which the LDEF was subjected. Preliminary comparisons of data in a previous review showed that it was possible to make meaningful intercomparisons between results obtained at different facilities (Harmon, et al., 1993*). Generally these comparisons were good and gave results to within 10-20%, although some analysis of data remains. These results clearly provide constraints for recent calculations being performed of the radiation environment of the LDEF (Armstrong and Colborn, 1993*). We are now anticipating a period of production of final activation results. An archive is being prepared jointly between NASA/Marshall and Eastern Kentucky University which will include gamma ray spectra and other intermediate results.

* LDEF Second Post-Retrieval Symposium, NASA CP-3194.

PREDICTIONS OF LDEF INDUCED RADIOACTIVITY AND COMPARISON WITH MEASUREMENTS

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ABSTRACT

As part of the calculational program in utilizing LDEF data to evaluate and improve the accuracy of current ionizing radiation environment models and related predictive methods for future LEO mission applications, model calculations have been carried out to compare with measurements of induced radioactivity produced by the nuclear activation of various materials on LDEF. Detailed features of the radiation exposure (e.g., anisotropy, altitude and solar cycle dependence) and spacecraft shielding (3-D geometry/mass model) are incorporated in the calculations to help insure that differences between the predicted and observed activations can be attributed to the ambient radiation environment uncertainties. Activation predictions and data comparisons have been made for metal samples (V, In, Ta, Ni, and Co) placed in various experiment trays, fission foils (^{238}U, ^{232}Th, ^{209}Bi, and ^{181}Ta) placed in several radiation dosimetry packages, pieces of the stainless steel trunions, and aluminum experiment tray clamps. The results provide a quantitative estimate of environment model uncertainties (trapped and galactic proton fluence levels, magnitude of trapped proton anisotropy) and also provide a consistency check for radiation model evaluations made using other LDEF data sets (viz., dose and LET spectra).

[1] Work supported by NASA Marshall Space Flight Center, Huntsville, Alabama.

STATUS OF LDEF RADIATION MODELING

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ABSTRACT

The current status of model predictions and comparisons with LDEF radiation dosimetry measurements is summarized with emphasis on major results obtained in evaluating the uncertainties of present radiation environment models. The consistency of results and conclusions obtained from model comparisons with different sets of LDEF radiation data (dose, activation, fluence, LET spectra) is discussed. Examples where LDEF radiation data and modeling results can be utilized to provide improved radiation assessments for planned LEO missions (e.g., Space Station Freedom) are given.

[1] Work supported by NASA Marshall Space Flight Center, Huntsville, Alabama.

^{10}Be IN TERRESTRIAL BAUXITE AND INDUSTRIAL ALUMINUM: AN LDEF FALLOUT

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ABSTRACT

Work has continued on the search for ^{10}Be on metals other than aluminum flown on LDEF. Much time-consuming extractive chemistry has been performed at Rutgers University on turnings obtained from the ends of two stainless steel trunnions for LDEF and the prepared samples will be run on the University of Pennsylvania accelerator mass spectrometer. These measurements together with the results of our investigation of the naturally-occurring ^{10}Be contamination in bauxite and industrial aluminums from different sources will be reported.

Meteoroid and Debris

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Status Of LDEF Contributions To Current Knowledge Of Meteoroid And Manmade Debris Environments And Their Effects On Spacecraft In LEO

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ABSTRACT

The analyses, which are currently being performed by the LDEF Meteoroid and Debris Principal Investigators and the other LDEF Meteoroid and Debris Special Investigation Group Members, of the data derived from the seven meteoroid and debris experiments that were flown on the LDEF and the post retrieval scans of the impact sites found on other experiment and LDEF surfaces will when they are completed result in many very significant contributions to our knowledge of the meteoroid and debris environments and the effects these environments can have on spacecraft in LEO. This paper provides a status report on the analyses that have been performed todate and the preliminary contributions indicated by these analyses. This paper also discusses new questions that have been raised by the completed analyses regarding these environments and their effects on spacecraft.

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ACTIVITIES AND PLANS OF THE METEOROID AND DEBRIS SPECIAL INVESTIGATION GROUP

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ABSTRACT

The LDEF Meteoroid and Debris Special Investigation Group (hereafter M&D SIG) was formed to maximize the data harvest from LDEF by permitting the characterization of the meteoroid and space-debris impact record of the entire satellite. Thus, our work is complementary to that of the various M&D PIs, all of whom are members of the SIG. This presentation will summarize current SIG efforts concerning four critical SIG goals: (1) identification of impactor origins based upon composition and mineralogy of residues, (2) characterization of small impact features, (3) reduction of impact feature imagery to derive projectile sizes and masses, and (4) preparation of a final M&D SIG report. This abstract is not intended as an exhaustive summary of M&D SIG activities, which are discussed in greater detail in accompanying abstracts.

METEOROID AND DEBRIS CHARACTERIZATION: Much more needs to be learned about the chemistry of residues in impact craters, especially as it applies to separating the orbital debris and meteoroid population into two distinct groups. This work is critically important because the average velocities of the two groups of particulates are so different (averaging ~7 and ~20 km/sec, respectively). Determination of the impactor-residue bulk major-element compositions is a first step in this characterization, and this work is being carried out in numerous labs [*e.g.*, 1, 2, 3]. In many cases, impactor vapor residues are all that remains of a dust grain; isotopic analysis by secondary ion mass spectrometry (SIMS) has proven to be a useful way to at least partially circumvent this problem [4,5]. Structural information must also be collected from impactor residues if we are to properly understand the origin of impacting particulates. Towards this end SIG members have developed techniques for the mineralogical analysis of appropriate impactor residues by transmission electron microscopy [6].

SMALL IMPACTORS: Several investigators have noted that for small particulates (<50 μm in diameter) orbital debris appears to dominate the crater populations on LDEF. These small impact features are deemed sufficiently important that the M&D SIG is assisting PIs in their characterization. The SIG has concentrated its efforts on LDEF structural members and experiment clamps [7,8].

IMPACT FEATURE IMAGERY REDUCTION: During and following LDEF deintegration the M&D SIG collected stereo imagery of all large impact features on LDEF. Extraction of impact feature diameters and depths from these images has not been simple. However, we have achieved some success in this effort [9], the results of which will be improved calculations of impactor diameters, masses and trajectories.

FINAL M&D SIG REPORT: Efforts are now underway to prepare a final report of the M&D SIG, which will serve as a guide to engineers and scientists, a record of the meteoroid and debris environment in LEO as it existed during the LDEF mission, and therefore a baseline for future LEO environment characterization missions.

M&D SIG MEMBERS not listed as authors of this report are: Martha Allbrooks and Dale Atkinson (POD Associates, Inc.), Don Brownlee (Univ. Washington), Fritz Bühler (Univ. Bern), Ted Bunch (NASA ARC), Vladimar Chobotov (Aerospace Corp.), Cassandra Coombs (POD Associates, Inc.), Gunther Eichhorn (Space Telescope Science Institute), Miria Finckenor (NASA MSFC), Fred Hörz (NASA JSC), Donald Humes (NASA LaRC), Don Kessler (NASA JSC), J-C Mandeville (CERT-ONERA), J. A. M. (Tony) McDonnell (Univ. Kent), Michael Mirtich (NASA LaRC), J. Derral Mulholland, Charles Simon (Institute of Space Science & Technology), Robert Walker (Washington Univ.), Alan Watts (POD Associates, Inc.), Jerry Weinberg (Institute of Space Science & Technology), Ernst Zinner (Washington Univ.) and Herb Zook (NASA JSC).

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MICROMETEOROIDS AND DEBRIS ON LDEF

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ABSTRACT

Part of the LDEF tray allocated to French experiments (FRECOPA) has been devoted to the study of dust particles. The tray was located on the face of LDEF directly opposed to the velocity vector. Crater size distributions have made possible the evaluation of the incident microparticle flux in the near-Earth environment. Comparisons are made with measurements obtained on the other faces of LDEF (tray clamps), on the leading edge (MAP) and with results of a similar experiment flown on the MIR space station.

The geometry of impact craters, depth in particular, provides useful information on the nature of impacting particles and the correlation with the chemical analysis of projectiles remnants inside craters make possible a discrimination between meteoroids and orbital debris. Emphasis has been laid on the size distribution of small craters in order to assess a cut-off in the distribution of particles in LEO. Special attention has been paid to the phenomenon of secondary impacts.

A comparison of flight data with current models of meteoroids and space debris shows a fair agreement for LDEF, except for the smallest particles : the possible contribution of orbital debris in GTO orbits to the LDEF trailing edge flux is discussed. For MIR, flight results show differences with current modeling: the possible enhancement of orbital debris could be the due to the contaminating presence of a permanently manned space station.

EXPERIMENTS AO 138-1/2

SMALL CRATERS ON THE METEOROID AND SPACE DEBRIS IMPACT EXPERIMENT

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ABSTRACT

Examination of the aluminum plates from the Meteoroid and Space Debris Impact Experiment (S0001) has been extended down to a crater diameter of 100 microns. Some aluminum plates from other experiments that were donated to the Meteoroid and Debris SIG were also scanned for small craters. At least one plate from each of the fourteen sides of the LDEF was examined. The depth and the shape of the small craters will be discussed.

Revised data on the large craters will be included.

A model of the near-Earth meteoroid environment will be presented.

EXPERIMENT NO. S0001

PARTICLE FLUX AS A FUNCTION OF POINTING DIRECTION AS DETERMINED FROM LDEF's STRUCTURAL-FRAME COMPONENTS BY THE METEOROID & DEBRIS SPECIAL INVESTIGATION GROUP

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ABSTRACT

INTRODUCTION: A major goal of the Meteoroid & Debris Special Investigation Group (M&D SIG) is to define the hypervelocity particle environment encountered by LDEF during its 5.7 year stay in low-Earth orbit (LEO). Over the past several years we have reported [1,2,3] on the frequency of craters ≥500 μm and penetration holes ≥300 μm in diameter on LDEF's structural frame and Teflon thermal blankets, respectively. Presently, members of the M&D SIG at the Johnson Space Center (JSC) are performing detailed scanning of LDEF structure-frame components (*i.e., Intercostals*) in the Facility for the Optical Inspection of Large Surfaces (FOILS laboratory). Sixty eight of the 72 *Intercostals* that were located around the periphery of LDEF (*i.e.,* Bays A-F) now reside at JSC; two *Intercostals* from each of the spacecraft's end-rings (*i.e.,* Bays A06 & A12 and F06 & F12) could not be removed from the spacecraft.

Each *Intercostal* (6061-T6 aluminum) exposed ~0.06 m^2, while an average row of six *Intercostals* exposed a total of ~0.36 m^2 in each of the 12 principal pointing directions. These *Intercostals* are being to define the relationship between pointing direction and particle flux in LEO. To date we have scanned 24 *Intercostals* (*i.e.,* two from each of LDEF's 12 rows; ~0.72 m^2). It is hoped that an additional one or two sets of 12 *Intercostals* can be completed in time for the 3rd LDEF Post-Retrieval Symposium.

DATA ACQUISITION: All scanning procedures and equipment are the same as in years past. Interested readers are referred to any of our previous reports [1,2,3] for details associated with either the equipment or procedures.

RESULTS: The cumulative size-frequency distributions of craters can be seen Fig. 1a, which depicts the average frequencies for the four main LDEF pointing directions (*i.e.,* 12 [north], 9 [east], 6 [south] and 3 [west]). Each curve represents the average of the main row from each direction plus the rows on either side (*i.e.,* west represents the average of Rows 2, 3 and 4). Such a plot is useful in revealing the overall trends associated with each of these four pointing directions. As expected, the forward-facing rows reveal the highest cratering frequencies, while the rearward-facing rows exhibit the lowest. Also, not surprisingly, the northern facing rows (1, 12 and 11) display a slightly higher overall flux than does its southern-facing counterparts, at least for craters >30 μm in diameter. This difference is most likely due to the fact that LDEF's velocity vector was yawed ~8° toward the Row-12 direction (*i.e.,* Rows 1, 12, and 11 pointed ~8° more into the velocity vector, while Rows 5, 6, and 7 were ~8° further removed from the velocity vector [5]). The elevated flux for the southern-facing rows below 30 μm is due to the unusually high frequency of small features that were previously documented on *Intercostal* F07F02 [3].

Fig. 1b depicts the relative production rates (*i.e.,* normalized to Row 9) for five selected diameter ranges. We are confident that our coverage is complete for all craters ≥30 μm in diameter so there should be no biases introduced as a result of incomplete scanning. Fig. 1b shows that the ratio of the production rate of impacts on the leading edge to that on the trailing edge varies depending on the impact-crater diameter. Comparing Rows 9 and 3, the ratio is 10:1 for the smaller features (*i.e.,*≥40 to <57 μm in diameter), yet shows a steady decrease (*i.e.,* ~8:1, 7:1, 6:1, and 3:1) as feature size increases (*i.e.,* ≥80 to <113, ≥160 to <226, ≥320 to <453, and ≥640 to <905, respectively). However, what can also be seen in Fig. 1b is that Row 9 does not possess the highest flux for all feature sizes. For the three largest size bins Row 10 exhibits the highest flux, while Row 8 is higher than Row 9 for the two largest sizes. If we compare the averages of the east- and west-facing directions the ratios range from ~8:1 to ~10:1 for the four smallest size bins, and drops to ~5:1 for the ≥640 to <905 μm size features. Is the large-particle population more isotropically distributed, are these differences related to the sources, and hence the associated velocities of the different particle-population sizes, or is this simply a statistical effect from the reduced number of impacts at successively larger diameters?

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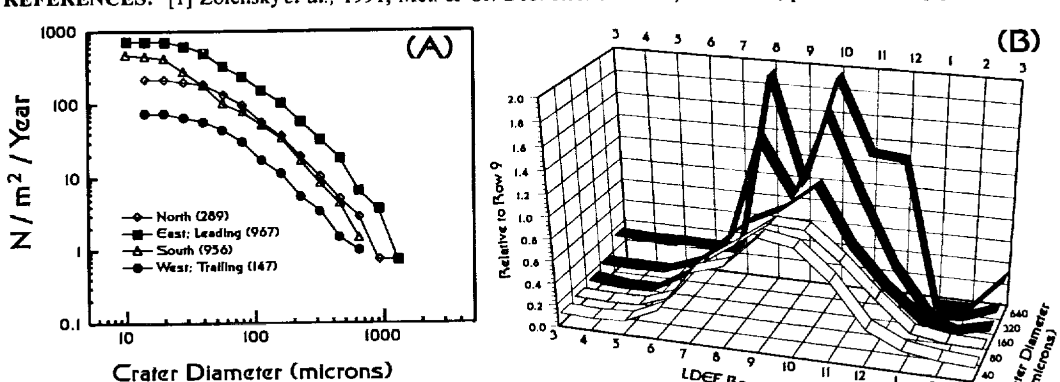

Figure 1. (A) Average crater frequencies for LDEF *Intercostals.* Numbers in parentheses () indicate number of data points in each line. (B) Relative impact frequency for selected crater diameters, with respect to Row 9, for the 12 main pointing directions of LDEF.

LONG-TERM MICROPARTICLE IMPACT FLUXES ON LDEF DETERMINED FROM OPTICAL SURVEY OF INTERPLANETARY DUST EXPERIMENT (IDE) SENSORS

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ABSTRACT

An optical survey of impact sites on electronic sensors of the Interplanetary Dust Experiment (IDE) that remained active during the entire LDEF mission has been extended to included all active sensors from row 3 (the west or trailing edge), the earth end and the space end, and 7-10 sensors from each of rows 6 (south), 9 (ram or leading side), and 12 (north). The ability to easily detect the optical signature of submicron and larger particle impacts on these surfaces, and the high counting statistics of this survey provide a large data set for comparison with other LDEF surveys and model predictions. This data set is particularly useful in showing long term trends in impact fluxes since the first year of impact data was electronically recorded. This situation allows the flux data to be divided into 3 long term time periods, the first year, the subsequent 4.8 years, and the entire 5.8 year orbital mission.

Comparisons of the survey data with scanning electron microscopic surveys by other LDEF investigators has confirmed an order of magnitude higher long term impact flux on the trailing side of LDEF during the first year in orbit compared to the subsequent 4.8 years. This result has serious implications for model predictions that rely on impact flux ratios where the trailing edge rate is used. While large swings in the impact flux rates on the leading side of LDEF were observed in the electronic data from the first year in orbit, the long term fluxes on the leading edge varied by less than 2%. Long term impact fluxes on the space and earth ends, and on rows 6 and 12, varied by less than a factor of 2.

Based on the IDE survey, an estimate of the total number of impacts on LDEF from 0.5 μm diameter and larger particles yields a value of ~7 x 10^6. This result will be compared to estimates derived by other investigators.

Sensor attrition (loss rate) due to catastrophic impact damage will also be reported. This will be one of the first verified reports of partial loss of space assets due to hypervelocity impact damage.

EXPERIMENT NO. A0201

PENETRATION RATES OVER 30 YEARS IN THE SPACE AGE

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ABSTRACT

Aluminium foils have been exposed by the author to the space impact environment over a considerable period, namely

1) on the US/UK satellite Ariel II (1963),
2) MFE on NASA's OSS-1 Shuttle Flight 1992, and
3) the Microabrasion Foil Experiment LDEF (1984 to 1990)..

Spacecraft measurements span 30 years of flux rate exposure to penetration detectors. Uniquely, in all three flights a common reference material has been deployed , hard temper rolled aluminium 1100 T6. Augmented by impact rates of craters aluminium louvres on the Solar Maximum mission (4) , they provide a unique constraint on the flux variations in an era where the satellite population has grown exponentially.

Results will be presented focussed on the resolution of LDEF's impact damage into natural and space debris components.

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EXPERIMENT NO. AO 023

LDEF INTERPLANETARY DUST EXPERIMENT (IDE) RESULTS

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ABSTRACT

The Interplanetary Dust Experiment (IDE) was designed to provide high time resolution detection of microparticle impacts on LDEF. The IDE detectors (which covered about one square meter of the surface of LDEF) were sensitive to particles ranging in size from about 0.2 microns to several hundred microns in diameter. Detectors were mounted on rows 3 (Wake or West), 6 (South), 9 (Ram or East,) and 12 (North), as well as the Earth and Space ends of LDEF. The time of each impact is known to an accuracy that corresponds to better than $\pm$ 1° in orbital longitude. The LDEF was gravity-gradient stabilized and magnetically damped. Thus, the orbital location of LDEF and the position vector of each detector panel normal is precisely known for each impact. Data were recorded for 11 1/2 months before the supply of magnetic tape was exhausted. The resulting dataset represents the most extensive record gathered of the number, orbital location, and direction of impacts due to small particles on a spacecraft in low Earth orbit.

Perhaps the most striking result from IDE was the discovery that microparticle impacts, especially on the Ram, North, and South surfaces, were highly episodic. Most such impacts occurred during Multiple Orbit Event Sequences (MOES), in which IDE detected impacts over a narrow range in orbital longitude which repeated, orbit after orbit, for many orbits. In addition, more than a dozen intense "spikes" were observed whose possible sources will be discussed. After removal of the MOES and spikes from the IDE dataset the remaining data show signatures which may be attributed to the general orbital debris background as well as natural micrometeoeroids, including Beta Meteoroids. Analysis of these data for signatures of meteor streams will be discussed. Finally, plans for data archiving and for future investigations based on these data will be discussed.

Other papers at this conference will present detailed discussions of (1) orbital parameters of debris rings determined from IDE data, (2) long-term flux rates and impact induced sensor losses, determined from optical examination of recovered IDE sensors, (3) chemical analysis of impact sites and contamination features on recovered IDE sensors, and (4) IDE sensor calibration and performance.

EXPERIMENT NO. A0201

THE ORBITAL CHARACTERISTICS OF DEBRIS PARTICLE RINGS AS DERIVED FROM IDE OBSERVATIONS OF MULTIPLE ORBIT INTERSECTIONS WITH LDEF

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ABSTRACT

During the first 346 days of the LDEF's almost 6 year stay in space, the metal oxide silicon detectors of the Interplanetary Dust Experiment (IDE) recorded over 15,000 impacts, most of which were separated in time by integer multiples of the LDEF orbital period (the so-called *multiple orbit event sequences*, or MOES). Several prominent MOES, of differing characteristics, have been selected for the current investigation. One such event is the sole significant MOES occurring on the trailing edge detectors, a low energy, low intensity event beginning only 4 hours after LDEF deploy and lasting approximately 10 days. A second event, the "May swarm," began on May 13, 1984 and lasted until June 7. It can be characterized as a long duration, low intensity (~3 impacts per orbit) event, with the impacts being recorded on the South and leading edge detectors, the majority occurring on the South. Another event, the "June 4A" event, began on June 4, 1984 and lasted two days. Of short duration and high intensity (~15 impacts per orbit), this event again saw impacts on the leading edge and South detectors, though in this case the majority of the impacts occurred on the leading edge.

A procedure, based on the work of Greenberg[1], has been developed and applied to the three MOES in an attempt to determine the orbital characteristics of the impacting particles. This paper will discuss these orbital characteristics and present a summary of the steps involved in their determination.

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EXPERIMENT NO. A0201

DETERMINATION OF ORBIT ELEMENTS FOR DEBRIS CLOUDS: THE LDEF LESSON IN CELESTIAL MECHANICS

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ABSTRACT

Early results of the analysis from the LDEF Interplanetary Dust Experiment (Mulholland *et al.* 1991) showed the existence of unexpectedly large and long-lived clouds of orbital debris. It was clear from an early date (*e.g.* Singer *et al.* 1991, Mulholland *et al.* 1992, Oliver *et al.* 1992) that the IDE data contained information on the orbits of the debris particles. Recent work drawing on the asteroidal close approach formalism of Greenberg (1982) has permitted us to realize that IDE-type observations permit a complete determination of the orbit of a debris cloud, with uncertainties that depend on the extent and temporal duration of the cloud and its differential inclination with the target spacecraft orbit. Examples drawn from the LDEF IDE data will be presented.

* * *

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EXPERIMENT NO. A0201

ORBITAL DEBRIS AND METEOROID POPULATION AS ESTIMATED FROM LDEF IMPACT DATA

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ABSTRACT

Since the LDEF was recovered in January 1990, many investigators have examined its surfaces and published data concerning the crater frequencies around the spacecraft. These data can be used to estimate the meteoroid and man-made debris population in low Earth orbit (LEO).

In this paper, a model describing the debris orbital parameter distributions will be introduced to explain the crater distribution measured on LDEF. Furthermore, a technique to properly convert the crater frequency to particle flux will be presented. For such a conversion, the ratio of particle diameter to crater diameter as a function of the surface orientation is needed, as well as the ratio of flux on a flat plate to the cross-sectional area flux.

By means of this technique, the meteoroid and debris population in LEO will be estimated. Discrepancies with existing models will be analysed.

HYPERVELOCITY IMPACT SURVIVABILITY EXPERIMENTS FOR CARBONACEOUS IMPACTORS

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ABSTRACT

We performed a series of hypervelocity impact experiments using carbon-bearing impactors (diamond, graphite, fullerenes, phthalic acid crystals, and Murchison meteorite) into Al plate at velocities between 4.2 and 6.1 km sec^{-1}. These tests were made in order to (a) determine the survivability of carbon forms and organic molecules in low hypervelocity impact, (b) characterize carbonaceous impactor residues, and (c) determine whether or not fullerenes could form from carbonaceous impactors, under our experimental conditions, or survive as impactors.

An analytical protocol of field emission SEM imagery, SEM-EDX, laser Raman spectroscopy, single and 2-stage laser mass spectrometry, and laser induced fluorescence (LIF) found that: (1) diamonds did not survive impact at 4.8 km sec^{-1}, but were transformed into various forms of disordered graphite, (2) intact, well-ordered graphite impactors did survive impact at 5.9 km sec^{-1}, but were only found in the crater bottom centers; the degree of impact-induced disorder in the graphite increases outward (walls, rims, ejecta), (3) phthalic acid crystals were destroyed on impact (at 4.2 km sec^{-1}), although a large proportion of phthalic acid molecules did survive impact, (4) fullerenes did not form as products of carbonaceous impactors (5.9-6.1 km sec^{-1}); fullerene impactor molecules mostly survived impact at 5.9 km sec-1 and, (5) two Murchison meteorite samples launched at 4.8 and 5.9 km sec^{-1}) show preservation of some higher mass polycyclic aromatic hydrocarbons (PAHs) compared with the non-impacted sample. Each impactor type shows unique impactor residue morphologies produced at a given impact velocity.

An expanded methodology is presented to announce relatively new analytical techniques together with innovative modifications to other methods that can be used to characterize small impact residues in LDEF craters, in addition to other acquired extraterrestrial samples.

HYPERVELOCITY IMPACT SURVIVABILITY EXPERIMENTS FOR CARBONACEOUS IMPACTORS: PART II

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ABSTRACT

In a continuing study of the effects of hypervelocity impact on carbonaceous impactors, we have launched diamonds (3 to 6 km sec^{-1}), phthalic acid (6.22 km sec^{-1}), Nogoya meteorite (6.19 km sec^{-1}), coal (5.95 km sec^{-1}), graphite (4.12 km sec^{-1}), and polycyclic aromatic hydrocarbons or PAHs (3 to 6 km sec^{-1}) into an Al plate. These tests were made in order to (a) determine the survivability of carbon forms and compounds under low hypervelocity impact, (b) characterize carbonaceous impactor residues, and (c) determine whether or not fullerenes could form from other carbonaceous materials on impact, under our experimental conditions.

Preliminary results from an analytical protocol of field emission SEM imagery, SEM-EDX, and 2-stage laser mass spectrometry indicate that some carbon forms and compounds do survive under low velocity impact. Both the Nogoya meteorite and graphite impacted samples showed preservation and destruction of polycyclic aromatic hydrocarbons as compared to non-impacted samples. The Nogoya meteorite showed a higher degree of alkylation as compared to Murchison and Allende meteorites[1]. Diamond samples launched at 3 and 6 km sec^{-1} show no apparent effect due to hypervelocity impact. There is no evidence for formation of higher mass compounds in the fullerene range (720 m/z) for graphite, diamond or Nogoya meteorite carbonaceous impactors examined too date. Analyses on phthalic acid (6.22 km sec^{-1}), coal (5.95 km sec^{-1}) and PAHs (3 to 6 km sec^{-1}) are in progress.

Work on these samples using the above techniques is on-going. In addition, micro Raman spectroscopy and electron energy loss spectroscopy (EELS) analyses will be utilized. This paper will summarize the results of the impact survivability experiments in the velocity range of 2-7 km sec^{-1}.

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COMPOSITIONAL ANALYSIS OF PROJECTILE RESIDUES ON LDEF INTERCOSTAL F07F02

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ABSTRACT

During the 69 month exposure to the particulate environment in low-Earth orbit (LEO), the Long Duration Exposure Facility (LDEF) sustained multiple, superficial meteoroid and orbital-debris impacts to external surfaces. These impact features were typically <1.0 mm in diameter; all craters ≥500 μm and penetrations ≥300 μm in diameter were located and documented by the Meteoroid & Debris Special Investigation Group (M&D SIG) during LDEF's deintegration in the Spring of 1990 [1]. Since this time, a more detailed examination of various LDEF hardware has been underway at the Johnson Space Center to augment the large-particle data with information from features as small as 10 μm [2,3]. Included in these detailed examinations have been the inspection of certain LDEF frame components (*i.e., Intercostals*). High-magnification optical examination of LDEF *intercostals* by the M&D SIG has determined that an anomalous number of craters ≤40 μm in diameter is present on *intercostal* F07F02 [3]. In an effort to understand this phenomena and to identify the source of these features, the M&D SIG has been analyzing these impact craters, the associated projectile residues, and contaminates by Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analysis (EDXA). The objectives are to evaluate the chemical variability and possible clustering of discrete particle types and determine their source(s). Detectable projectile residues were classified as either micrometeoritic or as man-made debris, while sources of surface contamination were identified when ever possible. These results are compared to those obtained on other examined regions of LDEF [4,5,6,7] in order to determine particle flux and compositional differences.

The occurrence of the various projectile types has been tabulated in histogram form and are illustrated in Figure 1, which displays the relative frequencies of micrometeoritic, man-made debris particles (*i.e.,* paint and electrical components), indeterminate, and contamination samples for the smaller size binds. Although only ten percent (to date) of the impacts on intercostal F07F02 have been analyzed, the trend toward a high occurrence of all types of particles is evident in the 20 to 40 μm size range. However, we note a particular increase in the relative amount of paint-type residues as compared to residues found on tray clamps and the gold surfaces from experiment A0187-1 [5,7]. SEM examination of the morphology shows that the depth to diameter ratios, the crater rim characteristics, and the residue remnants are similar within this suite of impact features. The chemistry of the paint-impact residues tend to be Si, Cl, Ti-rich paint, all exhibiting an absence of Zn. This may indicate that the projectiles originate from a common source and may be traveling as a dense cloud or group of orbital debris, since efforts to identify a source related to LDEF have been unsuccessful. However, until more analyses are conducted on LDEF's *intercostals* and the database expanded, conclusions will remain speculative.

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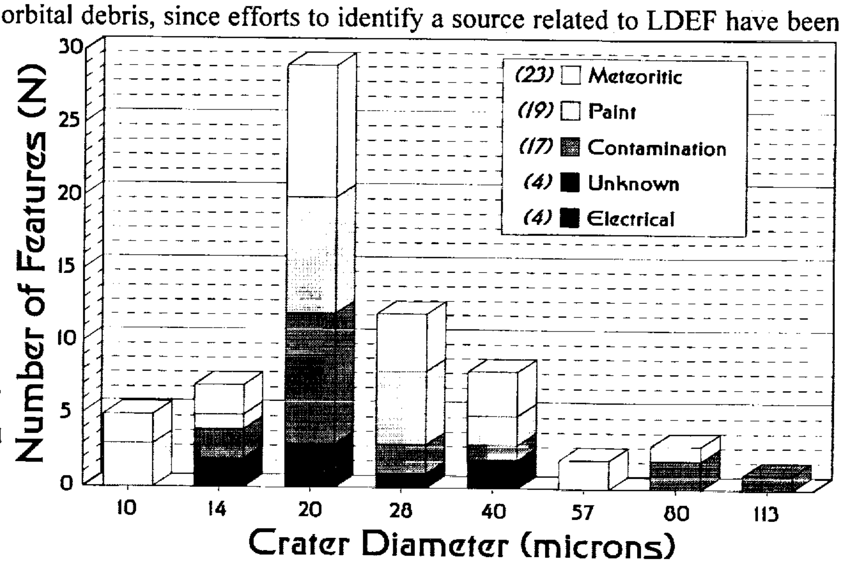

Figure 1. Relative occurrence of the various particle residues on *intercostal* F07F02.

OPTICAL AND ELECTRON MICROSCOPIC STUDIES IMPACTOR RESIDUES ON LDEF

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ABSTRACT

We report preliminary results of examination of impactor residues in craters in aluminum on the Long Duration Exposure Facility (LDEF). Our strategy is to analyze residues *in-situ,* to thin-section craters, and to remove residues from the craters using extraction replication. For *in-situ* analyses, we are evaluating optical photomacrography, UV fluorescence microscopy, reflectance IR microspectroscopy, and scanning electron microscopy (SEM). Thin-sectioning is carried out using an ultramicrotome. The selected crater is first trimmed until only a shell of the crater remains. The shell is embedded and sectioned using a diamond knife. Residues are extracted from craters using flexible collodion (cellulose nitrate). The extracted residues are removed from the collodion by washing with successive droplets of amyl acetate. Extraction replication was first employed to extract meteoritic residues from Solar Max craters [1,2].

UV fluorescence spectroscopy is being evaluated for rapid detection of residues in craters. Eighteen craters in aluminum clamps (B04-C03 and A11-C08) were examined under an optical microscope using a monochromatic UV (365 nm) source. Five of the craters displaying fluorescent features were examined using SEM in an attempt to correlate fluorescence with residues. In four of the craters, we were unable to correlate residues with areas of high fluorescence. The fluorescence seems to originate primarily from the crater rims and aluminum-rich ejecta, which suggests that defect structures in the aluminum itself or surface coatings on the aluminum may be responsible for the fluorescence. However, intense fluorescence in Crater A11-C08/9 was traced to a calcium-phosphorous-oxygen rich particle ($CaPO_4$?). SEM examination showed that B02-C01/1 contains chondritic material and B04-C03/4 contains euhedral (forsteritic) olivine fragments. Both of these craters are candidates for extraction replication.

Several craters containing meteoritic debris have been thin-sectioned. One has been examined using analytical electron microscopy (AEM). Preliminary findings on this crater have been reported [3], and we are now conducting a more detailed examination using a 200 KeV high-resolution analytical AEM. The residue is mostly an aluminosilicate glass with submicrometer to nanometer-sized Fe and FeNi spheres. Lattice fringe images and electron microdiffraction patterns reveal crystallographic order on a nanometer scale. These glass-like metal spheres presumably reflect the extreme quench rates associated with hypervelocity impact. Metallic silicon (Si) within the same glassy residue may have also been produced during impact, although contamination cannot be excluded. On the other hand, crystalline pentlandite ([Fe,Ni]S) appears to have survived without significant structural or chemical modification.

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ANALYSIS OF IMPACTOR RESIDUES ON LDEF CLAMP SURFACES BY SCANNING ELECTRON MICROSCOPY

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INTRODUCTION: In an effort to better understand the nature of particulates in low-Earth orbit and their effects on spacecraft hardware we are analyzing residues found in impacts craters on Long Duration Exposure Facility (LDEF) surfaces; we are initially concentrating on tray clamps because they represent a homogeneous material exposed in all LDEF pointing directions. All LDEF experiment trays were held in place by these chromic-anodized aluminum (6061-T6) clamps, each having an exposed area of approximately 58 cm^2. Half of LDEF's tray clamps are archived at the Johnson Space Center (JSC) by the Meteoroid & Debris Special Investigation Group (M&D SIG) and are available for study by qualified investigators; interested workers should contact the LDEF Curator at JSC (*i.e.*, Zolensky).

TECHNIQUE: Optical scanning of clamps, starting with Bay A Row 1 and working through the entire satellite, is being conducted at JSC to locate and document impacts as small as 30 μm in diameter. Following optical identification these impacts are inspected by Scanning Electron Microscopy/Energy Dispersive X-ray Analysis (SEM/EDXA) to analyze those features which contain appreciable impactor residues. Based upon the bulk composition of these residues, and using criteria developed at JSC, we have made a preliminary discrimination between micrometeoroid- and space-debris containing impact features. To date, 351 impacts on 61 clamps (*i.e.*, Bay A) have been analyzed by this technique. The results of our Bay A analysis are already published [1] in a NASA Technical Memorandum, and it is anticipated that a second volume (Bay B) will be available at the Conference. Within these catalogs the reported results of each impact includes (1) a secondary electron image, (2) associated parameters such as impact feature size and location, (3) an EDXA spectra of the residue, (4) the impactor type (if applicable), and (5) a curatorial number which will facilitate sample requests. In addition, this data is being input into the M&D SIG database, which documents all LDEF meteoroid and debris results, and is accessible to interested investigators [2].

RESULTS: The results indicate that unmelted fragments of debris particles should be present in selected impact craters, which can yield critical compositional and structural information, revealing the origin of individual debris impactors. These studies will serve to broaden our understanding of the low-Earth orbit particulate environment, as well as high-velocity particulate interactions with spacecraft.

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COMPOSITION AND FREQUENCY OF HYPERVELOCITY PARTICLES <1 MM IN DIAMETER IN LOW-EARTH ORBIT

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ABSTRACT

INTRODUCTION: We continue to analyze projectile residues associated with impact features from the "Chemistry of Micrometeoroid Experiment" (CME); details of the instrument are presented in [1]. Last year we reported [2] on the SEM-EDX analysis of all craters (*i.e.*, 199) >20 μm in diameter from the trailing-edge collectors (A03), and ~200 craters >75 μm in diameter from the forward-facing (Bay A11) aluminum 1100 surfaces. During the past year we have analyzed an additional ~400 craters from the A11 aluminum collectors.

COMPOSITIONAL CLASSES: As previously described [2,3], the distinction between natural and man-made impactors can generally be made with ease, and, in many cases, impactors can be assigned to compositional subclasses. Among the natural particles, chondritic compositions dominate, followed by monomineralic residues of either olivine or pyroxene, and Fe-Ni sulfides. Man-made particles of pure aluminum abound on the gold surfaces, yet a *miscellaneous* category was established that is dominated by paint flakes, but also includes metal alloys (*e.g.*, stainless steel), and Cu and Ag-containing electronic components. The relative flux of these particle types can be seen in Fig. 1a.

NO DETECTABLE RESIDUE: In Fig. 1a note that ~50% of all craters do not contain detectable residues, most likely due to loss by complete vaporization. Using mean impact velocities of 12 and 19 km/s for natural particles encountering the A03 and A11 surfaces [4], and the equation-of-state for aluminum 1100 and gold [5], one calculates similar peak pressures (Al - 430 GPa; Au - 460 GPa) for both CME surfaces using model projectiles composed of anorthosite [6]. Such pressures will lead to almost complete vaporization of anorthosite [6]. It is important to emphasize that aluminum projectiles cannot be detected on the A11 aluminum substrates (*i.e.*, a significant fraction of the *unknown* craters could be the result of aluminum projectiles).

PROJECTILE FREQUENCY: Using the above mean impact velocities for all craters resulting from natural impactors, and those of [7] for man-made particles (V_{A03} = 1.75 km/s; V_{A11} = 7.85 km/s) we converted the measured crater diameters into projectile masses using the equations of [1] for the gold surfaces, and those of [8] for aluminum collectors, assuming a projectile density of 2.7 g/cm^3. This conversion resulted in the cumulative mass-frequencies and fluxes for specific particle classes that are depicted in Fig. 1b. The relative frequency of the natural particle classes seems invariant with viewing direction. Furthermore, natural particles seem to dominate the forward-facing direction (A11), yet the flux of man-made particles equals, or exceeds the natural impactors for the trailing edge (A03). These data were modeled by [7] who concluded that a substantial population of presently unaccounted for debris sources must exist in highly elliptic, low-inclination orbits (typical orbits for transfer vehicles of geosynchronous payloads). If the modal frequency of man-made particles observed for the A03 surfaces were applied to establish the (possibly) missing aluminum impactors on the A11 surfaces, one would obtain more craters than have been observed. We have difficulties understanding these findings, as they seem to be inconsistent with considerations regarding particle dynamics, which require that the substantial population of aluminum impactors on the rear surfaces should somehow be manifested on the forward-facing surfaces [7].

CONCLUDING REMARKS: Relative frequencies of projectile types as inferred from the observed frequency of laboratory analysis versus crater size (Fig. 1a) may differ significantly from the relative and absolute frequencies based on projectile mass (Fig. 1b). The wide range of impact velocities required to determine projectile masses call for substantially different conversion factors of crater diameter to projectile mass. This may cause *small* and *low* velocity craters (Fig. 1b) to be associated with *massive* projectiles, resulting in an effective shift to the right, whereas a *large* crater assigned to *fast* projectiles would yield a relatively modest projectile mass, resulting in an effective shift to the left.

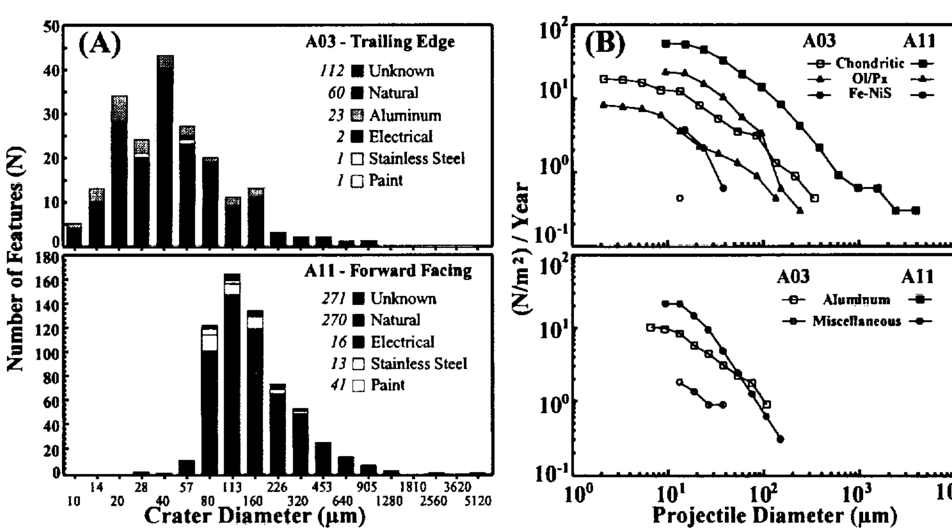

Figure 1. (A) Relative frequencies of the different compositional crater classes and (B) the absolute particle fluxes for the specific projectile types.

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DEBRIS AND METEOROID PROPORTIONS DEDUCED FROM IMPACT CRATER RESIDUE ANALYSIS

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ABSTRACT

This study is a further investigation of space-exposed samples recovered from the LDEF satellite and the French-Russian 'Aragatz' dust collection experiment on the MIR Space Station. Impact craters with diameters ranging from 1 to 900 µm were found on the retrieved samples. Elemental analysis of residues found in the impact craters was carried out using energy dispersive spectrometry (EDS) coupled to a scanning electron microscope. The analyses show evidence of micrometeoroid and orbital debris origins for the impacts. The proportions of these two components vary according to particle size and experiment position with respect to the leading edge of the spacecraft.

However, if the particle is travelling above a certain velocity, it vapourises upon impact and no residues are left. Simulation experiments carried out with an electrostatic accelerator indicate that this limit is about 14 km/s for Fe particles impacting Al targets. This chemical analysis cut-off may bias interpretations of the relative populations of meteoroid and orbital debris. Oblique impacts and multiple foil detectors provide a higher likelihood of detection of residues as the velocities involved are lower.

Bearing this bias in mind, some preliminary conclusions can be drawn from the analyses described here; for the size range defined earlier, on the LDEF trailing edge 85-90% of the impacts are apparently caused by micrometeoroids, the other 10-15% being debris particles - mostly larger than 3 µm in diameter - in elliptical orbits around the Earth. For Mir, the analyses indicate that micrometeoroids form 30% of impacts and debris 10%. However, 60% of the craters show no residue, so the definitive proportions of natural v. man-made particles are yet to be determined. Comparisons with current meteoroid and debris models (using ESAbase) are made.

EXPERIMENTS AO 138-1/2

MICRO-ABRASION PACKAGE CAPTURE CELL EXPERIMENT ON THE TRAILING EDGE OF LDEF: IMPACTOR CHEMISTRY AND WHIPPLE BUMPER SHIELD EFFICIENCIES

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ABSTRACT

The Micro-Abrasion Package experiment, (MAP, AO023) /1/ flown on LDEF by the University of Kent, consisted of double layer thin metallic film capture cells. These capture cells were situated on the north, south, east (leading), west (trailing) and space faces of the LDEF, with a combined exposed area of 0.6624 m^2. The capture cells consisted of aluminium foils with thickness' between 1.5 μm and 31.1 μm and brass foils between 5.0 and 12.0 μm.

This paper concentrates on the MAP section of the west face which provided an exposed area of 0.1472 m^2. Since the foils were situated on the trailing face of the LDEF, they were subjected to the lowest flux of particles. However, impactors require elliptical orbits in order to "catch up" with the LDEF and for orbital debris particles the maximum normal impact velocity on the trailing face will be 3.2 km/s. The west foils offer the greatest opportunity for intact capture of Interplanetary Dust Particles (IDP), and artificial particles and consequent chemical analysis using an X-ray Energy Dispersive Spectroscopic technique.

The Chemistry of Micrometeoroids Experiment (CME, AO187-1) /2/ indicated that 15% of their impacts on the trailing face were confirmed as being due to"catch-up" orbital debris. Thus the data presented in this paper will be important in clarifying the actual percentage of space debris to natural particles in the low Earth environment and can be directly compared to the CME data.

The west capture cells have yielded the crater depth to crater diameter ratio (T_C/D_C), the ratio of diameter of perforations converted to equivalent foil thickness (D_H/f_{max}), extensive chemical analysis and ellipticity measurements. Also, this study provides a more accurate knowledge of the flux and particle distribution. Examination of the crater morphology gives an indication of the velocity and direction of the impactors, from which it is possible to infer the mass and diameter of the projectiles, providing information on their origin. The results obtained have enabled the identification of the impacting particles and determination of the percentage of interplanetary and space debris particles. Future research on the European Retrievable Carrier (EuReCa) as well as other faces of the LDEF would be a natural progression of this work.

A comparison of the effectiveness of the capture cells, which are a form of Whipple bumper shield, with a single aluminium foil of equivalent thickness has also been made. This will have particular relevance to the design of the Space Station Freedom.

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SECONDARY ION MASS SPECTROMETRY (SIMS) ANALYSIS OF HYPERVELOCITY MICROPARTICLE IMPACT SITES ON LDEF SURFACE

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ABSTRACT

Two dimensional elemental ion maps have been recorded for hundreds of microparticle impact sites and contamination features on LDEF surface. Since the majority of the analyzed surface were metal-oxide silicon (MOS) impact detectors from the Interplanetary Dust Experiment, a series of "standard" and "blank" analyses are included. Hypervelocity impacts of forsterite olivine microparticles on activated flight sensors served as standards while stylus and pulsed laser simulated "impacts" served as analytical blanks.

Results showed that despite serious contamination issues, impactor residues can be identified in ~1/3 of the impact sites. While aluminum oxide particles cannot be detected on the aluminum surface, remnants of manmade debris impactors consisting of paint chips and bits of metal have been identified on surfaces from LDEF Rows 3 (west or trailing side), 6 (south), 9 (ram or leading side), 12 (north) and the space end. Higher than expected ratios of manmade microparticle impacts to total microparticle impacts have been identified on the space end and the trailing side.

A myriad of contamination interferences were identified and their effects on impactor debris identification mitigated during the course of this study. These interferences include pre-, post and in-flight deposited surface contaminants as well as indigenous heterogeneous material contaminants. Non-flight contaminations traced to human origins, including spittle or skin oils contributed significant levels of alkali-rich carbonaceous interferences. A ubiquitous layer of in-flight deposited silicaceous contamination varied in thickness with location on LDEF and proximity to active electrical fields even on a micro scale. In-flight deposited (low velocity) contaminants include urine droplets and bits of metal film from eroded thermal blankets.

EXPERIMENT NO. A0201

ISOTOPIC ANALYSES OF IMPACT RESIDUES FROM LDEF EXPERIMENT A0187-1

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ABSTRACT

We have performed ion micro-probe analyses of impacts into high purity gold (>99.99%) from LDEF experiment A0187-1. According to previous SEM-EDX studies [1], these impacts were classified into several categories. "Natural" and "chondritic" impacts have X-ray peaks of several elements such as Si, Mg, Fe, and Al. "Man-made" impacts mainly show Al signals. However, about half of all impacts give no signal of any elements other than Au.

Some of the "natural" and "chondritic" impacts contain significant amounts of projectile material, allowing us to perform isotopic measurements. We have measured Mg and Si isotopic ratios in two "natural" impacts (#104 and #280). In impact 104, projectile residue is located on the edge of the impact, while in case of impact 280, most residue can be found at the bottom of the impact crater. For ion micro-probe measurements, we developed a new sample preparation technique to invert the crater. This was done by pressing the Au against a clean quartz disk and then pushing the crater bottom with a needle, resulting in a flat surface. The measurements of Si and Mg isotopic ratios in impacts 104 and 280 yielded results that differ by only up to 13‰ from the normal solar composition and fall on the terrestial fractionation line. These results are interesting for two reasons: They prove that it is possible to measure isotopic compositions of impact residues with high precision and they indicate that these residues did not experience large mass-dependent isotopic fractionation during the impact event. Future studies will include measurements of H, C, N, and O isotopic ratios.

Another objective of this study was to determine whether any projectile material could be detected by SIMS in "unknown" impacts (i.e. impacts that did not give any X-ray signals). In previously studied samples from experiment A0187-2 [2,3], lateral SIMS scans across extended impacts clearly showed enhancements of elements attributed to projectile material, although no impact deposit could be detected by SEM-EDX analysis. One (impact 89), out of two "unknown" impacts studied, clearly shows enrichment of Al in a scan across the flattened crater. This impact can thus be classified as "man-made". As previously demonstrated [2,3], the ion micro-probe is in some cases clearly superior to conventional SEM-EDX techniques, especially for impacts which do not contain large amounts of projectile material.

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IMAGE AND COMPOSITIONAL CHARACTERISTICS OF THE "BIG GUY" LDEF IMPACT CRATER

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The largest impact crater on LDEF measures 5.2 mm in diameter and has a depth to diameter ratio of approximately 0.5. The "Big Guy" crater was located on tray H03, experiment M0001. Although this tray faced out into space, this particular impact occurred on an Al metal frame, which projected in the ram facing direction. Initial observations showed no obvious impact residue or ejecta common to some other craters, i. e., dark residues and streaks. Scanning electron microscopy indicated the presence of abundant Al-rich features within the crater, resembling mounds, with morphologies controlled by screw dislocations. Field emission scanning electron microscopy (FESEM) shows (a) Al target melt splash with textures indicating quenched molten Al and (b) Al melt spherules and the unusual Al columns with rounded tops (see above) which we call now "hoodoos" on the crater walls and rim. FESEM analyses show that the spherules and hoodoos contain (in addition to Al) Si, Mg, C, and O. Slightly darkened patches on the rim also have this composition.

The analytical protocol for Big Guy also included the application of Auger Electron Spectroscopy (AES) for major element mapping, and Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) for trace element and molecular mapping.

We infer from this preliminary investigation that Si, Mg, and some of the C represent impactor residue (although some of the C may be contamination). We are conducting further investigations of this important impact feature in order to gain better insight as to the origin of the impactor (IDP or debris) and the possible contamination component.

We thank James Adams, Naval Research Laboratory, for permitting us to examine the frame member from his LDEF experiment M0001.

MINERALOGY OF INTERPLANETARY DUST PARTICLE RESIDUES RECOVERED FROM LDEF IMPACT FEATURES

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ABSTRACT

INTRODUCTION: Impactor residues in materials exposed on the Long Duration Exposure Facility (LDEF) satellite are being characterized to establish the nature and abundance of meteoritic and orbital debris materials in the low-Earth orbit (LEO) environment [1], and also the effect hypervelocity impacts will have on spacecraft. In this study, simple techniques were developed for the study of selected chondritic (containing Si, Mg, Fe, ± Al, Ca, S, Mn, and Ni in appropriate amounts) impactor residues in shallow craters in gold plates, from LDEF experiment A0187 [2,3,4]. A detailed structural and compositional analysis of several of these impactor residues was performed utilizing transmission electron microscopy, energy dispersive spectroscopy, and electron diffraction. The immediate goal of this continuing work has been to determine the effects of the impact process on impactor mineralogy and mineral composition of chondritic interplanetary dust particles (IDPs), and to compare these impactor residues to chondritic IDPs collected from the stratosphere.

SAMPLE PREPARATION AND ANALYTICAL PROCEDURES: Residues from the interior of several craters in gold [2] were removed with a tungsten needle, mounted in EMBED-812 epoxy, and ultramicrotomed into 90 nm thick sections. Observation of the sections on carbon-coated copper grids was done by transmission electron microscopic techniques using JEOL 100CX and 2000FX analytical electron microscopes. Chemical analyses of crystalline areas were performed with a PGT System 4 energy dispersive X-ray (EDX) spectrometer and reduced with the PGT dedicated software, and a LINK EDX system and software. The structural state of all analyzed materials were assessed by electron diffraction, which proved to be a critical step, considering the non-crystalline nature of many materials observed.

RESULTS: We examined the mineralogy of residues from three impact features: nos. 102, 121, and 295. Impact residue 102 has very finely-divided crystalline clino- and orthopyroxene (En_{89-93}), showing abundant evidence of intense shock, these being planar deformation features, mosaicism, and, in some instances, evidence of recrystallization (120° grain intersections). The matrix consists of vesicular ferromagnesian glass. Spherical bodies of Fe-Ni (±Cr) metal and pyrrhotite abound locally, particularly at grain boundaries. Impact residue 121 contains fragmental grains of equilibrated olivine (Fo_{57-67}) orthopyroxene (En_{63-64}), Fe-Ni metal, and abundant glass. The olivine and pyroxene grains show abundant evidence of shock (see above for criteria). Impact residue 295 contains shocked, fragmental, equilibrated olivine (Fo_{56-71}) and orthopyroxene (En_{71}), Fe-Ni metal, and glass.

The compositions of olivines and orthopyroxenes in IDP residues 121 and 295 are equilibrated compared to anhydrous chondritic IDPs, and also Fe-rich compared to hydrous chondritic IDPs and the bulk of ferromagnesian minerals from anhydrous chondritic IDPs. They are also Fe-rich as compared to ferromagnesian minerals from partially melted chondritic IDPs [5], which are typically on the order of Fo_{90} and En_{90}. However, these ferromagnesian residue minerals are compositionally similar to those found in large (>100 µm) IDPs recovered from polar ices [6], which are also partially melted. The IDP residue from crater 102 appears to be less shocked and melted than 121 or 295. The compositional range of pyroxene in residue 102 is similar to that observed in hydrous chondritic IDPs, probably the most common variety [5]. We are continuing to search for more pristine IDP impactor residues in LDEF materials.

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QUANTITATIVE MICRO-NONDESTRUCTIVE EVALUATION

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ABSTRACT

Recent advances in measurement science permit the quantitative evaluation of elastic and geometric properties at and beneath the surface of materials. This paper presents examples of precision measurements to assess materials and their properties. The measurement technologies include radiography, ultrasonics and theromography. Images and quantitative elastic data are presented ranging from milli to micro to nano scale level of critical materials. Examples of images include metal-matrix composites, thin-film clad structures, volumetric microimaging of materials, laminography, and microfocus tomography. Since these same technologies may be of value to LDEF, this paper is presented to stimulate discussion and open the door for interlaboratory cooperation.

THE EFFECT OF IMPACT ANGLE ON CRATERS FORMED BY HYPERVELOCITY PARTICLES

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Abstract

The ability of the Space Shuttle program to retrieve satellites, such as LDEF and Solar Max, from earth orbit has allowed researchers to learn a great deal about the space environment. Upon retrieval of LDEF, NASA personnel of the Meteoroid & Debris Special Investigation Group identified more than 34,000 features caused by the hypervelocity impacts of micro-meteoroids/space debris. While it is unlikely that the micro-meteoroids/space debris could cause catastrophic structural damage to a spacecraft, they can cause extensive damage to windows, solar cells, protective coatings, and other more delicate components.

The Space Power Institute of Auburn University has conducted tests on the effects of impact angle on crater morphology for hypervelocity impacts. Copper target plates were set at angles of 30° and 60° from the particle flight path. For the 30° impacts, the craters looked almost identical to earlier normal incidence impacts. The only difference found was in the apparent distribution of particle residue within the crater, and further research is needed to verify this. The 60° impacts showed a marked differences in crater symmetry, crater lip shape, and particle residue distribution. The particle velocities ranged from 4 to 10 $km.s^{-1}$. This information is applicable to the determination of the directionality of the incident micro-meteoroid/space debris flux for various exposed LDEF surfaces.

This work was supported by NASA-Langley Research Center, which we gratefully acknowledge.

EXPERIMENTAL INVESTIGATION OF THE RELATIONSHIP BETWEEN IMPACT CRATER MORPHOLOGY AND IMPACTING PARTICLE VELOCITY AND DIRECTION

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ABSTRACT

Interpretation of the wealth of impact data available from the Long Duration Exposure Facility, in terms of the absolute and relative populations of space debris and natural micrometeoroids, requires three dimensional models of the distribution of impact directions, velocities and masses of such particles, as well as an understanding of the impact processes. Although the stabilised orbit of LDEF provides limited directional information, it is possible to determine more accurate impact directions from detailed crater morphology. The applicability of this technique has already been demonstrated (Newman et al, 1992; Mackay et al , 1993), but the relationship between crater shape and impactor direction and velocity has not been derived in detail.

We present the results of impact simulations:

1) impacts at micron dimensions using the Unit's 2MV Van de Graaf accelerator
2) impacts at mm dimensions using a Light Gas Gun
3) computer simulations using AUTODYN-3D

from which an empirical relationship between crater shape and impactor velocity, direction and particle properties may be derived. Such a relationship can be applied to any surface exposed to space debris or micrometeoroid particles for which a detailed pointing history is available.

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EXPERIMENT NO. A0 023

DETERMINING ORBITAL PARTICLE PARAMETERS OF IMPACTS INTO GERMANIUM USING MORPHOLOGY ANALYSIS AND CALIBRATION DATA FROM HYPERVELOCITY IMPACT EXPERIMENTS IN THE LABORATORY

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Apart from chemical analyses of impact residues on LDEF surfaces, a look at the morphology of impact features found on germanium surfaces can reveal information on particle parameters. The Lehrstuhl fuer Raumfahrttechnik (lrt) performs analyses of impact features found on germanium surfaces flown on LDEF in experiment A0187-2.

Hypervelocity impact experiments conducted at the lrt provide calibration data for impacts of particles with diameters from 10 to 100 microns and velocities between 5 and 20 kms-1.

Both laboratory data and the LDEF features may be used for analyses of crater cross-sections and crater volumes which are obtained using a three-dimensional laser topographer. Correlations between various geometry parameters and crater cross-section variations with particle speed are given together with analyses of morphology variations specific to brittle target materials.

Finally, the experimental data can be used for scaling of impact phenomena onto different surface materials, which were also present on the LDEF satellite, such as aluminum or gold.

COMPARISON OF HYDROCODE CALCULATIONS WITH MICRO-ABRASION PACKAGE (MAP) PENETRATION DATA DERIVED FROM THE SPACE, WEST, AND EAST FACES OF LDEF

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ABSTRACT

The continued analyses of penetrating impacts on MAP foils of Aluminium and Brass have produced data for several LDEF faces, i.e., Space, West, and East /1/. The parameters most critically assessed have been diameter of the penetration hole, D_h, and for semi-infinite targets the depth to diameter ratio of craters, D_c/T_c. From these data have been derived the density of the impactor, and from the crater morphology the impact angle relative to the MAP surfaces. The West face is valuable analysis for modelling purposes since the velocity range for space debris is known to be narrow, i.e., the geocentric velocity must be between 7.64 and 10.8 km/s. Since only the impactors in elliptical orbits can "catch-up" LDEF, there will be a greater opportunity to determine more accurately the origin of the impactor. The mass of the impactor may be inferred from the D_c/T_c or from the ballistic penetration limit of the foils. Hydrocode modelling of thin film penetrations have progressed for MAP foils and the derived parameters of D_h, foil thickness, density, velocity, and impact angle have been entered into the theoretical calculation matrix. A result of that work will be a comparison between previously accumulated data from D_h in hypervelocity accelerator tests, LDEF MAP foil measurements and Hydrocode calculations /2/.

In conjunction with other on-going investigations, an effort will be made to incorporate penetration data from LDEF Meteoroid & Debris database /3/ in the hydrocode computer analysis. Hypervelocity impact data will be folded into theoretical work investigating the effects of the normal component of velocity of both normal and oblique hypervelocity impacts. Combined with recently developed orbital dynamic models, depicting the velocity distribution of projectiles impacting the faces of LDEF, this will be utilized to establish the normal component of velocity of the most likely candidates. The outcome will be the continuation of the development of a coherent model begun by UKC-USS researchers to describe the penetration dynamics associated with LDEF MAP foils.

The ratio of natural to man-made particles will also be accurately determined by a continuing analysis of the Aluminium and Brass MAP foils. The results of hydrocode calculations will be utilised to compare the effects on the impact event when mass, density, velocity and impact angle are varied for both impactor and target. The results, both measured and calculated, will be compared with several penetration formulae at low impact velocities in the case of the West face and higher impact velocities in the case of the South and Space faces of LDEF. Hydrocode calculations will be employed to predict the penetration hole size from the particle parameters, and these predictions will be compared with both calibration and LDEF MAP foils data.

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EXPERIMENT NO. AO-023

DIMENSIONALLY SCALED HYPERVELOCITY PENETRATIONS OF TEFLON TARGETS

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INTRODUCTION: The Ultra Heavy Cosmic Ray Experiment (UHCRE) employed 16 experiment trays that pointed in nine of the 12 viewing directions available on LDEF. Each of these trays, as well as the SEEDS in Space experiment tray, were covered by ~200 μm thick thermal blankets that exposed ~1.17 m^2 of surface area, resulting in a cumulative surface area of ~20 m^2 [1, 2]. These blankets possessed literally thousands of craters and penetrations [2] that represent a unique opportunity to characterize the size frequency and flux of hypervelocity particles in low-Earth orbit. Interpretation of impact features on LDEF's thermal blankets is limited, however, because prerequisite impact simulations under laboratory conditions are lacking. We are currently conducting such experiments on behalf of the LDEF Meteoroid & Debris Special Investigation Group.

EXPERIMENTS: We impacted pure Teflon^{FEP} targets of varying thicknesses with soda-lime glass spheres (3175, 1000 and 150 μm in diameter) with the objective of determining an empirical relationship between the penetration-hole diameter (D_h), target thickness (T), and projectile diameter (D_p), as we had done earlier with aluminum targets [3]. In addition, several experiments were conducted using pristine LDEF thermal blankets. The LDEF thermal blankets are more complex composites [2], compared to monolithic Teflon^{FEP}, yet we see no differences in D_h of the respective penetration holes. Here we report on experiments that utilized projectile velocities of ~6 km/s; equivalent experiments at higher and lower velocities are in progress, after which, important issues related to velocity scaling will be addressed.

RESULTS: Figure 1 summarizes the penetration-hole diameters of all 6 km/s experiments performed to date. Note that unique solutions for D_p result (at constant velocity) from the measurement of D_h and T, and that projectiles of dramatically different sizes define a single curve. As a consequence, "dimensional scaling" of penetration holes is a valuable approach in extracting projectile dimensions from space-exposed surfaces. A variety of curve-fitting procedures were applied to the data points of Fig. 1, with the best fits resulting from a polynomial equation of the form:

$$\log_{10} y = a_0 + a_1 (\log_{10} x)^2 + a_2 (\log_{10} x)^3 + a_n (\log_{10} x)^n$$

where $y = D_p/T$ and $x = D_h/T$. For Teflon^{FEP} the following coefficient apply: $a_0 = -0.485$; $a_1 = 0.667$; $a_2 = 0.562$; $a_3 = -0.230$; $a_4 = 0.518$; $a_5 = 0.021$; $a_6 = -0.661$; $a_7 = 0.415$, and $a_8 = -0.075$. We also determined that the ballistic limit for pure Teflon^{FEP} is at $D_p/T = 0.17$ under the prevailing conditions. Therefore, incipient penetration of the LDEF thermal blankets (T≃ 190 μm [2]) is caused by (glass) particles >32 μm at 6 km/s.

CONCLUSIONS: Fig. 1 and similar, more extensive dimensionally-scaled data of penetrations in aluminum [3] demonstrate that differential size-frequency distributions of projectile sizes can be obtained from a population of penetration holes, akin to craters [*e.g.*, 4], yet replacing the traditional approach based on ballistic limit considerations [5] that typically yields a single, cumulative datum only.

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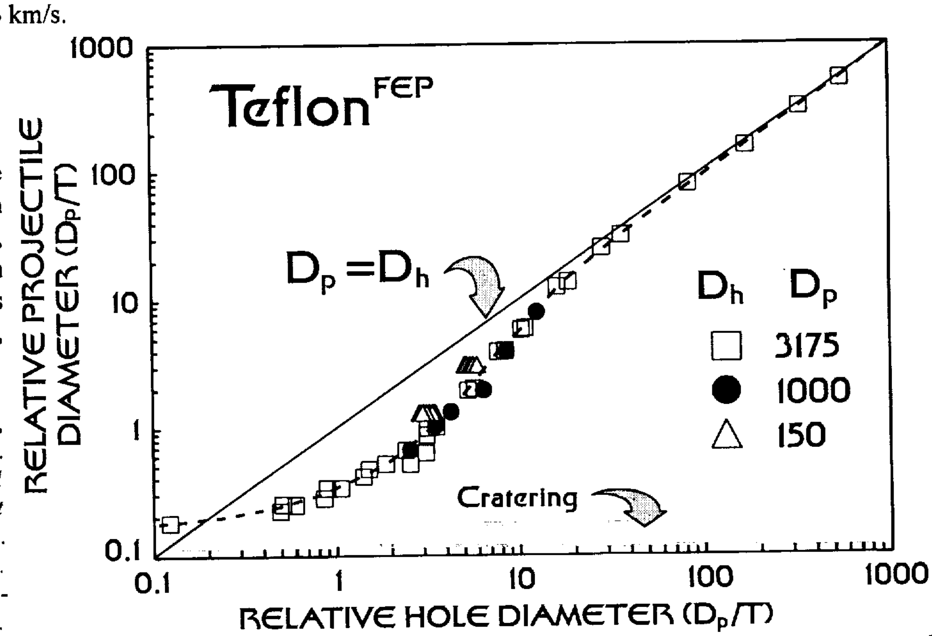

Figure 1. Diameter of penetration hole (D_h) versus projectile diameter (D_p) for Teflon targets of thickness (T). Projectiles were all soda-lime with a velocity of ~6 km/s. Solid line represents the case of D_p=D_h.

DIMENSIONAL SCALING FOR IMPACT CRATERING AND PERFORATION RESULTS

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ABSTRACT

The LDEF Meteoroid and Debris Special Investigation Group (M&D SIG) is chartered to collect and interpret the LDEF impact data and apply the interpretations to verify and update the environment and impact effects models. Since the largest sources of LDEF data are impacts into aluminum and FEP Teflon, the M&D SIG's efforts will be hampered without broadly applicable scaling laws. Consequently, the M&D SIG is supporting these POD Associates, Inc. efforts to develop new generic physics-based scaling laws. The results of these efforts are being presented in this paper.

This paper summarized the development of two physics-based scaling laws for describing crater depths and diameters caused by normal incidence impacts into aluminum and TFE Teflon. The equations for perforations in aluminum and TFE Teflon for normal impacts are then described. Lastly the effects of non-normal incidence on cratering and perforation are summarized.

DERIVATION OF AN ALUMINIUM-TEFLON MARGINAL PERFORATION CONVERSION FACTOR USING LDEF DATA FROM THE ULTRA HEAVY COSMIC RAY EXPERIMENT AND THE LDEF INTERCOSTALS

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ABSTRACT

The Ultra Heavy Cosmic Ray Experiment (UHCRE) occupied the largest area on LDEF of all the experiments flown, and was situated on all the peripheral faces of LDEF except rows 3, 9 and 12. Nine sections of these thermal blankets were scanned at the University of Kent, yielding a wealth of data on cumulative flux values and upper and lower penetration holes sizes, right down to the marginal perforation limit.

The intercostal structural members of LDEF along the peripheral faces represented a total exposed surface area of almost 7.5m^2 and were manufactured from 6061-T6 aluminium beams. About 0.83m^2 of these were analysed in great detail at NASA JSC, yielding data on crater diameters down to about 10 microns.

It is possible to utilise data from both these surfaces to derive a marginal perforation conversion factor from Teflon to aluminium. By comparing the perforation limits on the UHCRE surfaces with fluxes on the intercostals a marginal perforation conversion factor shall be derived. This factor is almost certainly velocity and density dependent and therefore requires that velocity enhancement due to LDEF's orbital motion is accounted for, as well as the relative fluxes of micrometeoroids and space debris, which will vary considerably between each peripheral face.

Reasons for obtaining an adequate penetration conversion factor for Teflon are plentiful. It will enable a more efficient investigation of the particulate environment to be made, as a more straightforward comparison between surfaces recovered from future space experiments and those already analysed will be possible. A conversion factor is one step towards the determination of a full penetration relationship describing Teflon which will be particularly convenient given the common application of Teflon as a thermal protection cover for satellites. Furthermore, if the behaviour of Teflon under a hypervelocity impact is better known quantitatively, its effectiveness as a shield for particulate matter will automatically be better understood, and will thus perhaps allow its usage as a shielding material in addition to a thermal control cover.

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EXPERIMENT NUMBERS A0023, A0178 and LDEF STRUCTURAL FRAME

THE DENSITY OF LDEF'S HYPERVELOCITY IMPACTORS

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ABSTRACT

Although the hypervelocity impact process erases almost all the information regarding impactor shape, velocity, density and angle of approach, clues nevertheless remain. On LDEF's large area and throughout a 5.75 year exposure which is randomised regarding **interplanetary dust** and yet well determined regarding **orbital components (space debris?)**, searches for clues have proven fruitful.

We examine:

- crater depth to diameter ratios
- crater ellipticity
- thin foil perforations compared with crater diameter.

Data shows that the interplanetary component, which is the dominant incident on the space and west faces, is of low density for particulate dimensions above 5 microns; this is estimated to range from 0.5 to 1.5 g cm^{-3}. At smaller dimensions there is evidence for increasing density. On the East (ram direction) faces, large particles again have low density but there is a high flux of small dense particulates.

Using two-dimensional and three- dimensional Autodyn Hydrocode Modelling (1) , we present data from which, when folded with modelling of the dynamic properties of the Earth's dust envelope (2) , we can begin to decode the physical properties of the impactors.

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EXPERIMENT NO.AO 023

METEOROID & DEBRIS SPECIAL INVESTIGATION GROUP STATUS OF 3-D CRATER ANALYSIS FROM BINOCULAR IMAGERY

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ABSTRACT

During the three-month deintegration of LDEF, the Meteoroid & Debris Special Investigation Group (M&D SIG) generated ~4,500 digital, color stereo-image pairs of impact related features from all space-exposed surfaces. Currently these images are being processed at the Johnson Space Center (JSC) Houston, Texas, to yield more accurate feature information (*e.g.*, the crater depth and diameter with respect to the original target surface). An earlier paper [1] describes the theory and practice of determining this 3-dimensional feature information from stereo imagery, while a second paper [2] describes some of the problems and solutions encountered during the algorithm development.

Currently, matching data points (tie-points) are selected by an analyst from each of the images for several points on the original target surface and on impact related features (*i.e.*, crater rim, crater bottom, etc.). A procedure has been developed for using these initial tie-points as "seeds" for a modified cross-correlation between the two images. This correlation results in a greatly increased number of tie-points within the crater, along with a confidence indicator for each tie-point. This approach permits a large number of tie-points to be used as inputs to the parametric fit, while minimizing the man-hour intensive task of manual tie-point selection.

Both the user-selected tie-points and the tie-points resulting from the seeded cross-correlation are used as inputs to the analysis software. The tie-points on the original target plane are used to define the ambient surface and to correct all tie-points for any rotations and Y-offsets. A parabolic fit is performed to determine an approximation of the central axis of the crater, and then an iterative downhill simplex minimization method of a least-squares sixth-order curve is applied to determine the best fit to the available data. The intersection of this sixth-order curve with the ambient plane is used to define the diameter of the crater at the ambient surface, while the distance of the center of this sixth-order curve from the ambient surface is utilized to define the feature depth. In order to account for varying accuracy caused by differences in image quality and asymmetrical craters, a confidence indicator is output along with the crater depth and diameter. Although the software is currently functional, it is still undergoing accuracy and limits testing.

This paper will address the details of the current approach, the algorithm's shortcomings and advantages over other approaches, and plans to fully automate the analysis procedure by eliminating the requirement for seed tie-points.

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Materials

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SUMMARY AND REVIEW OF LDEF MSIG RESULTS

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Major materials findings obtained during LDEF post-flight investigation of the past three and one-half years will be reported. The summary of findings to date will review results for thermal protection paints, composites, metals, adhesives, polymeric thin films, contamination, and environments definition. Reaction rates of materials exposed to atomic oxygen will be presented. These results will be compared with results from other flight experiments. Recent results from examination of Kevlar will be presented. Results useful for model verification and comparison against ground based facilities will be specifically highlighted. Potential areas for future work will be described. Finally, a rationale for a second long term flight experiment will be presented.

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Summary of 1993 LDEF Materials Analysis at Boeing

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Results will be reported for selected paints, heat shrink tubing, silvered Teflon, adhesives, and molecular contaminant films examined since the last LDEF symposium. Optical properties, surface characterization, and recession rates will be determined as sample configuration allows. Results from these measurements will be put in context with earlier LDEF results and related to practical engineering uses. The status of Boeing's environments definition predictive models will be reported and examples of engineering use of these models provided. A brief description of LDEF materials reports completed and in work will also be presented.

Boeing Defense & Space Group activities were funded by NASA Langley Research Center contract NAS1-19427, Task 8

LDEF POLYMERIC MATERIALS: A SUMMARY OF LANGLEY CHARACTERIZATION

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ABSTRACT

The NASA Long Duration Exposure Facility (LDEF) provided a novel environmental exposure of a wide variety of polymeric materials. The effects of atomic oxygen, ultraviolet and particulate radiation, meteoroid and debris, vacuum, contamination, and thermal cycling on these materials have produced a data base unparalleled in the history of research on space environmental effects. A representative collection of LDEF polymers were assembled at the Langley Research Center for chemical analysis. This paper summarizes work on these materials from the initial planning stage to the present.

While the majority of specimens came from Langley's Row 9 materials experiments S0010 and A0134, other samples from several LDEF locations were provided by individual principal investigators. Thus, polymeric materials which experienced different LDEF environments were examined.

The results of ultraviolet-visible and infrared, thermal, x-ray photoelectron, and solution property measurements as well as optical, scanning electron, and scanning tunneling microscopies are discussed. Effects of increased atomic oxygen fluence toward the end of the LDEF mission, contamination, and post-flight specimen changes are addressed. While results indicate no significant change in bulk chemical properties of most polymers, changes in surface chemistry could be dramatic. The intent of this paper is to add to the body of knowledge on space environmental effects on materials made possible by the remarkable LDEF spacecraft.

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SURFACE ANALYSIS OF MATERIALS FROM NASA-LDEF SATELLITE

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ABSTRACT

The flight and recovery of the LDEF has provided a wealth of information on the long term space environmental effects of a variety of materials exposed to the low earth orbit environment. The extent of atomic oxygen erosion, ultraviolet radiation / degradation, and contamination effects on a variety of materials has been characterized using several surface analytical techniques including XPS (x-ray photoelectron spectroscopy), AES (Auger electron spectroscopy), SEM (Scanning electron microscopy), and contact angle analysis. The results of analyses of aluminum tray clamps with two thermal control paints, carbon fiber / polymer matrix composites, and a micrometeoroid impact on aluminum will be presented and discussed. Organic silicon was detected on the near-trailing and trailing edge tray clamps whereas inorganic silicon was detected on the leading edge samples. Carbon 1s curve fit analysis showed a distinct difference between A276 and Z306 paints on the leading edge compared to the trailing edge samples. The first ten months of the LDEF mission resulted in detectable changes in the carbon fiber / epoxy matrix composites based on a detailed analysis of the carbon 1s photopeak region. XPS analysis of the region near the visible micro-crater supports impact by a meteoroid. [Research supported by NASA - LaRC]

SPACE ENVIRONMENTAL EFFECTS ON POLYMER MATRIX COMPOSITES AS FUNCTION OF SAMPLE LOCATION ON LDEF

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ABSTRACT

This paper presents the results of a study of various aspects of space environmental effects on different polymer matrix composites as a function of angular location on the LDEF. Specific issues that have been addressed include the variation in absorptance/emittance and the possible effects of contamination and atomic oxygen. In addition the erosion yield measured for different composites as a function of circumferential position is presented and the erosion results compared to the standard cos $\theta^{1.5}$ model. Again, the possible effects of contamination are discussed. Finally, impact damage due to micrometeoroids/debris is examined in terms of the surface pitting that occurs and interior damage observed. The application of this data to design of composites and protective coatings is described together with some coating data derived from the recently returned UTIAS materials experiment that flew on STS-46.

The Characteristics of Thin-Film Polymers Exposed to the Low Earth Orbit Environment

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Polymer materials recovered from LDEF have been examined to characterize the change in properties due to exposure to the low earth orbit environment. In this study we provide test results for thin-film, low density polyethylene specimens using DMA, DSC, WAXS, and FTIR procedures. Due to the position of the experiment, these specimens were not exposed to erosion from direct impact atomic oxygen; yet, measurements reflect the combined effect of atomic oxygen in the presence of ultraviolet radiation. A set of control specimens were annealed to increase crystallinity. These specimens provide a basis to differentiate the change in crystallinity due to thermal cycling from the change due to atomic oxygen. Viscoelastic characteristics of these materials have been measured through DMA. The constitutive behavior for these materials is nonlinear; consequently, we developed a DMA methodology for nonlinear viscoelastic characterization of thin-film materials. Furthermore, we extend the DMA analysis to examine the activation energy associated with the relaxation processes.

THE EFFECT OF SIMULATED LOW EARTH ORBIT RADIATION ON POLYIMIDES

BY

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Spacecraft in low earth orbit are subjected to significant levels of high energy radiation, including UV and VUV wavelengths. The effects of UV radiation are enhanced over those at the surface of the earth, where the only incident wavelengths are greater than 290 nm. In low earth orbit the incident UV wavelengths extended below 290 nm into the VUV region, where the Lyman-α emissions of atomic hydrogen occur at 121 nm. In addition to electromagnetic radiation, in low earth orbit polymer materials may also be subjected to atomic oxygen particle radiation, which will result indirect oxidation of the polymer.

Thus, polymeric materials for space applications must exhibit a resistance to radiation damage by VUV and atomic oxygen. One class of materials which have this characteristic are the polyimides.

Polyimides are prepared from the reaction of a tetracarboxylic acid dianhydride with a phenylene diamine, with final cure over night at 300 ° C .

As part of a materials evaluation program for space applications, we have studied the effects of UV-VUV induced degradation processes in polyimides. Thermal Gravimetric Analysis was also used to determine the weight loss due to thermal degradation in an oxidising environment. The studies involve the photogeneration of radical species in the polymer matrices as the initial steps in the degradation process. In this paper molecular level information for the initial stages of the photodegradation processes obtained from ESR , FTIR and UV-Visible spectroscopies, will be discussed. The synergistic effect of radiation and atomic oxygen on polyimide surfaces, assessed using Scanning Electron Microscopy (SEM) and X-ray Photoelectron Spectroscopy (XPS), will be also considered.

The ESR study revealed the formation of a carbon centred radical. The radical concentration as a function of irradiation time and also the stability of this radical have been investigated under different environments.

The changes in the relative intensity of the asymmetric carbonyl stretch at 1780 cm^{-1} in the FTIR spectrum as a function of irradiation time suggests that the degradation of polyimides is by ablation from the polymer surface. Similarly, the UV absorption spectrum revealed a shift in the absorption with irradiation time. This might be related to the reduction in the electron density due to the dissociation of the imide linkage. An XPS study of the polyimide exposed to VUV radiation and atomic oxygen showed that oxidation takes place on the polymer surface.

THE SURFACE PROPERTIES OF FLUORINATED POLYIMIDES EXPOSED TO VUV AND ATOMIC OXYGEN

BY

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A need exists for high temperature (200-300°C) stable, flexible polymeric film and coating materials that have high optical transparency in the 300-600 nm region of the solar spectrum for applications in the space components, such as insulation blankets, solar cells and thermal control coating systems. Although, several classes of polymers are available which are transparent and colourless, such as polyesters or aliphatic polyimides, these materials have limited long-term thermal stability. On the other hand, commercially available aromatic polyimides are thermally stable, however they have poor transparency in visible region of the solar wavelength of interest for space applications. Furthermore, the transparency of these commercial polyimides is reduced dramatically after exposure to space environment. Several series of linear aromatic polyimide films having maximum optical transparency have been prepared by St. Clair et al (1). The optical transparency was achieved by using highly purified monomers and the incorporation of meta-linked diamines, bulky electron-withdrawing groups and flexible linkages into the molecular structure in order to reduce the electronic interactions between polymer chains (2).

As part of a materials evaluation program for space application, we present in this paper results of surface analysis of polyimides of this type exposed to a simulated low earth orbit environment of VUV and atomic oxygen. X-ray photoelectron spectroscopy was used to monitor the effect of atomic oxygen, VUV alone and the atomic oxygen and VUV in combination. It was found that atomic oxygen causes extensive damage to the polymer surface, while VUV alone causes minimum damage to the polymer surface.

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Collection and Review of Metals Data Obtained from LDEF - Experimental Specimens and Support Hardware

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Test data are available from many types of metals flown on LDEF in various applications and under a wide range of exposure conditions. Metals flown on LDEF include gold, aluminum, copper, stainless steel, nickel, tungsten, tantalum, titanium, iridium, osmium, platinum, zirconium and various alloys and metal matrix composites. Data previously reported from a number of investigators will be reviewed, augmented with results of measurements from testing support hardware at Boeing, and correlated with atomic oxygen and solar ultraviolet exposure levels. Performance evaluations will be made for these materials under the exposure conditions experienced. Conclusions concerning the suitability of specific metals for the applications evaluated along with suggestions for further space testing will be presented.

Boeing Defense & Space Group activities were funded by NASA Langley Research Center contract NAS1-19427, Task 8

MEASUREMENTS OF THE OPTICAL PROPERTIES OF THIN FILMS OF SILVER AND SILVER OXIDE

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ABSTRACT

Thin films of silver are efficient getters of atomic oxygen, but are largely unaffected by molecular oxygen. Conversion of silver to silver oxide produces dramatic changes in optical and electrical properties. The effect has been used by several groups since 1970 to study atomic oxygen naturally produced in the upper atmosphere. Our group has employed the method to measure angular scattering distributions of 5eV atoms at surfaces in orbit and to measure the attitude stability and offset of the LDEF spacecraft. Use of the silver films for quantitative purposes requires a fuller understanding of the properties and peculiarities of the silver/oxygen/silver oxide system. Optical measurements made on silver films exposed in space and at the University of Alabama in Huntsville oxygen atom beam facility will be discussed.

ATOMIC OXYGEN STIMULATED OUTGASSING (A0034): SUMMARY OF RESULTS AND LESSONS LEARNED

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ABSTRACT

Thermal control coatings, contaminant collector mirrors, and optical windows from the passive LDEF Experiment A0034 have been investigated, providing evidence for the relative role of atomic oxygen in the stimulation of volatile outgassing products. These analyses have indicated varying degrees of influence on respective material elements resulting from interactions with atomic oxygen, solar ultraviolet radiation, and outgassing deposition in the leading and trailing-edge thermal vacuum environment of LDEF. A summary of results is discussed for each of the six types of thermal control coatings flown. Retrospective considerations based on these results and the various types of laboratory observations derived from flight specimen investigations are reviewed. These considerations include evidence of post-flight air bleaching of coatings, the effects of the combined space environment, and the unanticipated sensitivity of both collected contaminants and the contaminant collector optics to the space environment. Relevant results of associated ground testing are presented, including ultraviolet and atomic oxygen stimulated effects in material fluorescence, atomic oxygen reactivity of deposited contaminant films, and the evidence of ultraviolet and thermal-vacuum effects in stimulated outgassing and altered deposition.

EXPERIMENT NO. A0034

ATOMIC OXYGEN INTERACTIONS WITH PROTECTED ORGANIC MATERIALS ON THE LONG DURATION EXPOSURE FACILITY (LDEF)

By

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ABSTRACT

The Long Duration Exposure Facility (LDEF) has provided an excellent opportunity to understand the nature of directed atomic oxygen interactions with protected polymers and composites. Although there were relatively few samples of materials with protective coatings on their external surfaces on LDEF, analysis of such samples exposed to high-fluence directed atomic oxygen has enabled an examination of the shape of atomic oxygen undercut cavities at defect sites in the protective coatings. Samples of aluminized polyimide Kapton and protective coatings on graphite epoxy composites have allowed comparison with models of atomic oxygen interaction processes to yield some degree of quantification of the controlling interaction processes. Such processes include reaction probabilities at 4.5 eV and at thermally accommodated energies, degree of thermal accommodation upon first impact, and angular distribution of scattered atomic oxygen. The use of the LDEF results along with computational modeling provide valuable insight into the determination of in-space durability of protected organic materials based on ground laboratory thermal energy atomic oxygen test results. Comparisons of LDEF results with computational modeling of atomic oxygen attack of polymers at defect sites in protective coating will be presented.

ANALYSIS OF THE SURFACE COATINGS AND FILMS ON THE THERMAL CONTROL SURFACES EXPERIMENT (TCSE), No. S0069

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ABSTRACT

The Thermal Control Surfaces Experiment (TCSE) carried a wide variety of thick and thin film thermal control materials into orbit on it's unforeseen 5.8 year mission in low earth orbit (LEO) on the LDEF. Material types flown on TCSE range from ceramic inorganic materials (Z-93, YB-71, D-111) to organic materials (S13G/LO, A276, Tedlar, Z302 and metallized films of silver/FEP). In addition several samples of A276 and Z-302 were overcoated with clear films of silicone as atomic oxygen protective coatings.

Extended exposure to the LEO environment of solar VUV, solar UV, particle radiation, atomic oxygen (AO), contamination, and thermal cycling had an effect on all materials that were on the TCSE. Exposure to the LEO environment not only had an effect on the reflectance of the exposed materials causing changes in their solar absorptance and diffusivity, but also caused changes in their mid Infrared (IR) absorptance characteristics. These changes in IR absorptance indicate basic changes in the molecular structure of these materials.

This paper presents the results of the surface analysis of the TCSE flight materials including UV-VIS-NIR, FTIR, elemental and molecular spectroscopy techniques. Physical analysis include optical, SEM, electrical and thermo-mechanical techniques.

TREND ANALYSIS OF IN-SITU SPECTRAL REFLECTANCE DATA FROM THE THERMAL CONTROL SURFACES EXPERIMENT (TCSE)

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ABSTRACT

The Thermal Control Surfaces Experiment (TCSE) on the LDEF was a comprehensive experiment that combined in-space measurements with extensive pre- and post-flight analyses of thermal control surfaces to determine the effects of exposure to the low earth orbit (LEO) space environment. The TCSE is the first space experiment to directly measure in-situ total hemispherical reflectance of thermal control surfaces in the same way they are routinely measured in the laboratory. In-space optical measurements performed by the TCSE offer the unique opportunity to perform a trend analysis on the performance of materials in the space environment. Trend analysis of flight data provides the potential to develop an empirical prediction model for some thermal control surfaces. For material research, trend analysis of the TCSE flight data can provide insight into the damage mechanisms of space exposure.

Trend analysis for the TCSE samples has been limited to those materials that were not significantly eroded by the atomic oxygen (AO) environment. The performance of several materials on the LDEF mission were dominated by AO effects. Trend analysis was performed on both the detailed spectral reflectance measurements (in-space, pre-flight, and post-flight) and on the integrated solar absorptance (α_S).

Results of the trend analysis for the six selected TCSE materials will be presented along with the spectral flight data. Possible degradation and effects mechanisms will be discussed to better understand and predict the behavior of these materials in the LEO space environment.

WHISKER/CONE GROWTH ON THE THERMAL CONTROL SURFACES EXPERIMENT #S0069

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ABSTRACT

An unusual surface "growth" was found during scanning electron microscope (SEM) investigations of the Thermal Control Surface Experiment (TCSE) S0069 front thermal cover. This "growth" is similar to the cone type whisker growth phenomena as studied by G. K. Wehner (Univ. of Minn.) beginning in the 1960's. Extensive analysis has identified the composition of the whiskers as most likely a silicate type glass. Sources of the growth material are from outgassing products from the experiment and the oxygen, which occurs naturally at these orbital altitudes in the form of neutral atomic oxygen. The highly ordered symmetry and directionality of the whiskers is attributed to the long term (5.8 year) stable flight orientation of the LDEF.

EXPERIMENT NO. S0069

DURABILITY OF REFLECTOR MATERIALS IN THE SPACE ENVIRONMENT

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ABSTRACT

Various reflector configurations were flown as part of the LDEF A0171 experiment. These reflectors were samples provided by OCLI and Cascade, and consisted of coated aluminum, enhanced aluminum, coated silver, and a silver alloy. These samples have been evaluated for changes in reflectance due to 5.8 years in the space environment. The reflector materials have also been evaluated using ellipsometer, SEM, and ESCA analysis techniques.

EXPERIMENT NO. A0171

FOUR SPACE APPLICATION MATERIAL COATINGS ON THE LONG-DURATION EXPOSURE FACILITY (LDEF)

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ABSTRACT

Four material coatings of different thicknesses were flown on the LDEF to determine their ability to perform in the harsh space environment. The coatings, located in the ram direction of the spacecraft, were exposed for 10 months to the Low-Earth Orbit (LEO) environment experienced by the LDEF at an orbit of 260 nautical miles. They consisted of: Indium Oxide (In_2O_3), Silicon Oxide (SiO_x), clear RTV silicone, and Silicone with Silicate-treated Zinc Oxide (ZnO). These coatings were flown to assess their behavior when exposed to atomic oxygen and to confirm their good radiative properties, stability, electrical conductivity, and resistance to UV exposure.

The flown samples were checked and compared with the reference unflown samples using high-magnification optical inspection, ESCA analysis, weight and dimensional changes. These comparisons indicated the following.

The 1000Å SiO_x coating eroded uniformly, with minor changes in its radiative properties. The 100Å of In_2O_3 coating eroded completely down to the Kapton® backing, with resultant losses of reflectance. The RTV-615 showed erosion, with carbon (C) content losses, while the Si remained constant, with the oxygen (O) concentration doubling. The RTV-615 silicone with K_2SiO_3 -treated ZnO changed from flat to glossy white in appearance. It lost C, the surface was etched, and increased its O content. The upper layers showed no remaining Zn or K. Losses of reflectance occurred within certain wavelength bands.

It was not possible to evaluate the experimental oxygen reaction rate using the calculated atomic oxygen fluence of 2.6×10^{20} atoms/cm^2 for the exposure of these coatings during the flight. The bakeout of the coatings was not carried out prior to the flight. Hence, the coating weight and dimensional included losses by outgassing products.

Composite Protective Coatings for Space Applications

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Successful use of composites in space depends on their ability to survive long-term exposure to atomic oxygen, ultraviolet radiation, charged particle radiation, thermal cycling, and micrometeoroid/space debris. The atomic oxygen environment is especially severe for unprotected composites surfaces in low Earth orbit. Ram facing unprotected graphite/epoxy flown on the 69-month Long Duration Exposure Facility (LDEF) mission lost up to one ply of thickness (0.005 inches) which resulted in significant decreases in mechanical properties. Several composite protective coatings were flown on LDEF including sputtered SiO_x/nickel, A-276, Boeing Materials Specification 10-60 (TiO_2 pigmented polyurethane), Z-306, ZnO silicone, TiO_2, and leafing aluminum. Results from the testing and analysis of the coated and uncoated composites flown on LDEF's leading and trailing edges have provided the baseline for determining the effectiveness of protectively coated composites in space. In addition to LDEF results, results from Shuttle flight experiments and ground based testing will be discussed

The development and presentation of this paper was funded by NASA Langley Research Center contract NAS1-19427, Task 8

C-2

STRUCTURE AND PROPERTIES OF POLYMERIC COMPOSITE MATERIALS DURING 1501 DAYS OUTER SPACE EXPOSURE AT "SALYUT-7" ORBITAL STATION

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ABSTRACT

These are the results of the comprehensive study of properties of glass fiber reinforced plastics, organic fiber reinforced plastics, carbon fiber reinforced plastics, hybrid composites based on epoxy compounds for aircraft construction after exposure to the outer space up to 1501 days at "Salyut-7" orbital station.

The work is aimed at showing up the behavior of polymeric composite materials (PCM) under a long-term stay on the near-earth orbit, at determining the ageing mechanism, at evaluating the outer space effect and variations of strain-stress response. Both the conditions of exposure and the composition of PCM under study are determined. After a run of tests in the outer space the standard strain and strength parameters, mass loss, density, changes of thickness have been estimated. The study with electronic microscopy, the dynamic mechanical analysis (DMA) and the estimation of thermal extension within a wide temperature range have been made.

The PCM binder post-cure main dominant process takes place under a long-run effect of the outer space factors. The level and the degree of post-cure depend on the composition and structure of composite, on the technological characteristics, on the cross-linking degree, on the maximum temperature of thermal cycles and exposure time. The binder post-cure well effect the PCM mechanical parameters. The strength response of the composites taken at room temperature is not decreased after 456-1501 days in the outer space and even increased under room temperature but for the organic fiber reinforced plastics.

For the separate PCM specifications the processes of post-cure and restructuring resulted in a decrease of dynamic shear modulus in a glassy state of a binder.

The character of distribution is varied under bending load from transverse crack to stratification as the result of consolidation of the irradiated hybrid composites surface layer exposed to thermal cycles. The increase of inner tensions for hybrid composites with the different linear thermal expansion coefficients is the negative effect of the post-cure process. The importance of this effect depends on the thermal cycles amplitude.

In unprotected PCM surfaces facing the incoming flow of atomic oxygen, microparticles and cosmic garbage the processes of pickling and microerosion take place with a maximum initial speed of exposure. It's worth taking into account the body effects such as moisture and low molecular products dissorption after 100-300 days of thermal cycling in the vacuum of the near-earth orbit when estimating the PCM total mass losses.

The overmolecular order in the binder volume is improved and the structure of undersurface layer of PCM is loosen exposured to the outer space according to microscopy data, to DMA and other methods. The microcracks are formed on the surface of plastics exposured to thermal cycles what, anyhow, doesn't affect substantially the mechanical parameters of PCM during 1501 days of natural tests. The majority of the outer space effects observed are attenuated when the open surface of plastics is screened either with aluminum foil or other plastic layers.

The pooled data are of great importance when constructing the elements of PCM for the external sheath of the spacecraft, selecting materials with the specified properties and possible to predict for a long-term operation.

OVERVIEW OF THE LDEF MSIG DATA BASING ACTIVITIES

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ABSTRACT

The Long Duration Exposure Facility (LDEF) and the accompanying experiments were composed of and contained a wide variety of materials, representing the largest collection of materials flown in low Earth orbit (LEO) and retrieved for ground-based analysis to date. The results and implications of the mechanical, thermal, optical and electrical data from these materials are the foundation on which future LEO space missions will be built. The LDEF Materials Special Investigation Group (MSIG) has been charged with establishing and developing data bases to document these materials and their performance to assure not only that the data are archived for future generations but also that the data are available to the spacecraft user community in an easily accessed, user-friendly form. This paper will give an overview of the current LDEF Materials Data Bases, their capabilities and availability. An overview of the philosophy and format of a developing handbook on LEO effects on materials will also be described.

ATOMIC OXYGEN DESIGN SUPPORT: DATABASE AND SYSTEM ANALYSIS TOOL

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ABSTRACT

We are conducting a multi-year, atomic oxygen technology development task. The task involves investigating the effects and interactions of low earth orbit atomic oxygen (AO) on spacecraft materials and components. The program's data are being made widely available to NASA, DoD, universities, and industries. Data are available through two elements: a computer-hosted, on-line database and a 486 microcomputer-hosted design tool.

The database contains all ground- and flight-generated AO data. It is part of a relational database system and is available to users nationwide over INTERNET. Powerful embedded software tools enable users to query, reduce, compare, and analyze the data. The database stores text and graphics data. The graphics data include digitized photographs, ESCA plots, charts, and other graphical representations. Where raw data exist for charts and graphs, the database system stores the data and recreates the charts and graphs with simple user command input. The database system is designed to be compatible with other NASA systems, such as MAPTIS.

The design tool integrates AO data and interaction models and spacecraft environments, geometry, and orbits into a single, desktop analysis tool. The underlying environmental models are accepted and used extensively by the science and engineering communities. The architecture of the tool allows any improvements and enhancements of the underlying models to be easily and quickly integrated. The AO data integrated into the tool is derived from the JPL Space Environment and Effects (SEE) Program. The development of the tool was funded by NASA and DoD. Future support from the SEE Program will continue to integrate new data into the tool.

DEMONSTRATION OF LDEF DATA IN THE M/VISION MATERIALS SOFTWARE SYSTEM

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ABSTRACT

NASA has selected PDA Engineering's M/VISION materials software system as one of two formats for the Long Duration Exposure Facility (LDEF) Materials Database. NASA has made the LDEF Materials Database available at no charge to the international materials community in the M/VISION format which is based on the evolving PDES/STEP standard for product data exchange. M/VISION allows users an efficient means to manipulate and visualize LDEF data locally.

PDA will have a poster presentation in which we have information about M/VISION and the LDEF data stored in the system. On the day of the NASA presentation entitled "Overview of the LDEF MSIG Database Activity", PDA will have an engineering workstation on our poster table and we will be demonstrating access, comparison and manipulation of the LDEF data.

EOIM-3

AN OVERVIEW OF THE EVALUATION OF OXYGEN INTERACTIONS WITH MATERIALS III EXPERIMENT: SPACE SHUTTLE MISSION 46, JULY-AUGUST 1992.

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ABSTRACT

The interactions of the ambient atomic oxygen in the low-Earth orbit environment with spacecraft materials have been the subject of several flight experiments and extensive ground based testing and experiment over the past 11 years. The effects of these interactions have been shown to be significant for long lived spacecraft such as Space Station Freedom and resulted in significant materials changes for externally exposed materials. The data obtained from previous flight experiments, augmented by limited ground based evaluations, have been used to evaluate hardware performance and to select materials. Questions regarding the accuracy of this data base remain, principally due to the accuracy of ambient density models used in predicting the short term ambient density required for computing materials reaction rates. An experiment entitled Evaluation of Oxygen Interactions with Materials III (EOIM-III) has been developed to obtain benchmark reaction rate data and was flown on Space Shuttle Mission 46 (STS-46). Ambient density measurements were made through the use of a calibrated mass spectrometer during the sample exposure. Combining these data with ambient density predictions produced an assessment of reaction rate data accuracy as well as reaction rate data on a large number of spacecraft materials. Additional information on ambient atmosphere interactions with various surfaces were obtained that is of interest in defining spacecraft local induced environments. A summary of payload design and operations, STS-46 flight history and the results of EOIM-III will be presented.

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EOIM-III MISSION AND INDUCED ENVIRONMENTS

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ABSTRACT

Quantitative interpretation of the materials reactivity measurements made in any space flight experiment requires complete and accurate definition of the space environment exposure. This paper presents a detailed definition of the space environment exposure for the Evaluation of Atomic Oxygen Interactions with Materials III (EOIM-III) flight experiment. The atomic oxygen fluence is estimated in three different ways. First, ambient oxygen atom measurements were made using a mass spectrometer that was calibrated before and after the mission in the high quality low-Earth orbit environment simulator (high-speed neutral oxygen atom beam system) at Los Alamos National Laboratory. Second, oxygen atom fluence was estimated directly from Kapton film erosion, as corrected for configuration interactions produced by the sample holder. Third, the RUNFLUX program was used to calculate oxygen atom fluence using the as flown Space Shuttle trajectory and solar activity parameters recorded during Space Shuttle Mission 46 (STS-46) at the Space Environment Services Center (National Oceanics and Atmospherics Administration), to account for the magnetic substorm activity observed during EOIM-III. Our best estimate of the oxygen atom fluence as of this writing is $2.2 \pm 0.1 \times 10^{20}$ atoms per square centimeter. In addition, the solar ultraviolet exposure history of the EOIM-III payload was determined by analysis of the as flown orbit and vehicle attitude combined with daily-average solar ultraviolet and vacuum ultraviolet fluxes produced by the Upper Atmosphere Research Satellite during STS-46. The thermal history of the payload as reported by several thermocouple sensors placed behind selected samples and on the EOIM-III payload structure is also presented. Finally, estimates of the EOIM-III contamination environment made both by in-flight measurements and by post-flight surface analysis of selected samples will be reported.

SPACECRAFT MATERIALS STUDIES ON THE AEROSPACE CORPORATION TRAY ON EOIM-III

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ABSTRACT

A passive tray was flown on the Effects of Oxygen Interaction with Materials experiment on STS-46 (EOIM-III) with 82 samples from The Aerospace Corporation. A variety of advanced materials related to potential uses on future spacecraft were included for evaluation representing optical coatings, lubricants, carbon/carbon composite protective coatings, graphite protective coatings, thermal control materials, and some samples of current materials. An overview of the available results from the investigations on these materials will be presented, particularly on the erosion of carbon/carbon and black Kapton samples.

EXPOSURE OF LDEF MATERIALS TO ATOMIC OXYGEN: RESULTS OF EOIM III

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ABSTRACT

The third Effects of Oxygen Atom Interaction with Materials (EOIM III) experiment flew on STS-46 from July 31 to August 8, 1992. The EOIM-III sample tray was exposed to the low-earth orbit space environment for 58.55 hours at an altitude of 124 nautical miles. The sample tray was exposed to a total atomic oxygen (AO) fluence of 1.99x1020 atoms/cm2. Five samples previously flown on the Long Duration Exposure Facility (LDEF) were included on the Aerospace experimental tray: (1) Chemglaze A276 white thermal control paint from the LDEF trailing edge (TE); (2) S13GLO white thermal control paint from the LDEF TE; (3) S13GLO from the LDEF leading edge (LE) with a visible contamination layer from the LDEF mission; (4) Z306 black thermal control paint from the LDEF TE with a contamination layer; and (5) anodized aluminum from the LDEF TE with a contamination layer.

This paper investigates the response of these materials to atomic oxygen exposure, and compares the results of the EOIM III experiment to the LDEF mission and to ground-based atomic oxygen exposure studies.

ATOMIC OXYGEN DOSIMETRY MEASUREMENTS MADE ON STS-46 BY CONCAP-II

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Abstract.

With increasing flight duration and the possibility of a permanent facility in space, long-term monitoring of material degradation due to atomic oxygen is increasing in importance. Reliance on models to determine the fluence of atomic oxygen is not only necessarily complex but also imprecise due to the strong dependence of oxygen concentration on day/night, latitude and solar activity. The traditional method for determining the gas phase species densities at low pressure, mass-spectroscopy is not only expensive but is limited in the area that it can monitor. Our group has developed a simple and inexpensive dosimeter to measure the atomic oxygen fluence via the change in resistance as the sensor element is gradually oxidized. The sensors consisted of thin-film circuit elements deposited on a suitable substrate. Four-point resistance measurements being used to monitor the change in resistance.

IN FLIGHT RESISTANCE MEASUREMENTS ON HIGH TEMPERATURE SUPERCONDUCTING THIN FILMS EXPOSED TO ORBITAL ATOMIC OXYGEN ON CONCAP-II (STS-46)

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ABSTRACT

$Y_1Ba_2Cu_3O_{7-x}$ high T_c thin film samples prepared at three different laboratories were exposed to 5 eV atomic oxygen in low Earth orbit on the ambient and 320° C hotplate during the first flight of the CONCAP-II experiment carrier.

The resistance of the thin films was measured in flight during the oxygen exposure and heating cycle. Superconducting properties were measured in the laboratory before and after the flight by the individual experimenters. Films with good superconducting properties, and which were exposed to the oxygen atom flux, survived the flight including those heated to 320° C (600K) with properties essentially unchanged, while other samples which were heated but not exposed to oxygen were degraded. The properties of other flight controls held at ambient temperature appear unchanged and indistinguishable from those of ground controls, whether exposed to oxygen or not.

RESULTS OF MATERIALS EXPOSURE TO LEO ON STS-46 WITH COMPARISON TO LABORATORY SIMULATION*

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ABSTRACT

Samples have been characterized after exposure to both simulations and the actual LEO environment. Materials exposed aboard LDCE-2 and 3, as well as EOIM-III include polymers, thin films of aluminum, diamondlike carbon, diamond, and indium tin oxide, as well as bulk graphite, graphite/boron nitride and carbon-carbon composites. Samples exposed to asher simulations using an air+oxygen gas mixture excited to plasma state by application of RF power are compared with those exposed to the actual LEO environment. Optical studies using spectrophotometry and ellipsometry (VASE) show changes absorbance and lowered specular reflectance. Microstructural changes include surface roughening and erosion as studied by Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM).

*Research supported by NASA-Lewis Research Center Grant NAG-3-95.

AN OVERVIEW OF MSFC INVESTIGATIONS ON EOIM-3

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ABSTRACT

The Evaluation of Oxygen Interaction with Materials Experiment, third flight, or EOIM-3 flew on the Space Shuttle mission STS-46 July 31 - August 8, 1992. EOIM-3 represented a joint effort of several NASA centers, contractors, and universities.

This array of active instrumentation and material exposure sub-assemblies was integrated as a Shuttle cargo-bay pallet experiment for investigating the effects of orbital atomic oxygen on candidate space materials. MSFC's contribution to this experiment included several passive exposure trays of material specimens, constant stress and constant strain sheet material exposure fixtures, the Atomic Oxygen Resistance Monitor (AORM) for actively monitoring atomic oxygen flux levels, and specimens of Chemglaze A276 and Z306 coatings for the EOIM-3 variable exposure mechanisms. As a result of approximately 40 hours of spacecraft velocity-vector oriented exposure during the later phases of the STS-46 mission in Low Earth Orbit (LEO), materials of the EOIM-3 experiment were exposed to an atomic oxygen fluence of approximately 2.0×10^{20} atoms/cm2.

An overview is presented of the technical approaches and results from analyses of the MSFC flight specimens, fixtures, and the AORM. Post-flight characterizations of these exposed materials in comparison to pre-flight measurements have provided atomic oxygen erosion rates and other quantitative indicators of relative LEO stability. The relative influence of detected contamination and solar ultraviolet radiation are discussed. Comparisons with relevant LDEF data are also reviewed.

EFFECTS OF ATOMIC OXYGEN ON POLYMERIC MATERIALS FLOWN ON EOIM-3

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ABSTRACT

Diverse polymeric materials, including several variations of Kapton, were flown on STS-46 as part of the Evaluation of Oxygen Interaction with Materials Experiment (EOIM-3). These materials were flown in the cargo bay and exposed to the space environment July 31 - August 8, 1992, including 40 hours of direct atomic oxygen impingement. The atomic oxygen exposure was approximately 2 x 10^{20} atoms/cm^2.

Polymeric materials flown on EOIM-3 include Kapton H, Kapton HN, carbon-impregnated Kapton, Kapton with plasma polymerized silicon oxide coating, aluminized Kapton with indium tin oxide coating, Tefzel ETFE, Lexan, FEP and TFE Teflon, bulk Halar and PEEK, S383 silicone and Viton elastomeric seal material. Analyses performed included thickness measurements using Dektak and eddy current methods, mass loss, resistance, permeability, hardness, and FTIR.

Two constant stress fixtures and two constant strain fixtures loaded with Kapton HN flew on EOIM-3. Aluminum was vapor-deposited in a dot pattern on the underside of the Kapton. The dots were used as locator sites for light-section microscope measurement of the Kapton thickness to the tenth of a mil. Pre- and post-flight measurements were made at over 30 locations to measure stretching or creep of the Kapton as well as variations in atomic oxygen erosion. Also located on the constant stress fixtures were smaller samples of Kapton underneath the stressed sample. These samples were analyzed for atomic oxygen scattering. Silver/Teflon tape was used to affix the smaller Kapton sample to the fixture.

Previous EOIM missions on STS-5 and STS-8 and the Long Duration Exposure Facility also contained polymeric material samples. Data from these previous flights are shown for comparison, as well as ground simulation of space environment effects using both thermal energy flow tubes and 5 eV neutral AO beam facilities. Reaction efficiencies for the various atomic oxygen exposure conditions are discussed.

THERMAL CONTROL MATERIALS ON EOIM-3

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ABSTRACT

Thermal control paints, anodized aluminum, and beta cloth samples were flown on STS-46 as part of the Evaluation of Oxygen Interaction with Materials Experiment (EOIM-3). These materials were flown in the cargo bay and exposed to the space environment July 31 - August 8, 1992, including 40 hours of direct atomic oxygen (AO) impingement. The atomic oxygen exposure was 2×10^{20} atoms/cm^2.

The thermal control paints flown on EOIM-3 include Chemglaze A-276, Z-306, Z-93, YB-71, as well as variations of zinc oxide, zinc orthotitanate, and doped silica, and five paints provided by the Lord Chemical Corp. The majority of these samples were passively exposed to the space environment, though the A-276 and Z-306 were also included in the Solar Ultraviolet (UV) and Variable Exposure Trays. Z-93 and YB-71 were flown on the 60 and 120 °C heated trays as well as the passive trays. Optical property measurements of absorptivity, emissivity, spectrofluorescence, and bi-directional reflectance are presented for each paint.

Several variations of anodized aluminum were flown. Chromic acid anodize, sulfuric acid anodize, and boric/sulfuric acid anodize flew on all three heated trays as well as the passive trays. The post-flight optical properties are within tolerances for these materials. Also flown were two samples of yellow anodized aluminum. The yellow anodized aluminum samples darkened noticeably. The edge covers and half-moon covers flown on various samples were made of chromic acid anodized aluminum.

Samples of aluminized and unaluminized beta cloth, a fiberglass woven mat impregnated with TFE Teflon, were flown with passive exposure to the space environment. Data from this part of the experiment is correlated to observations from LDEF and erosion of the Teflon thin film samples also flown on EOIM-3 and LDEF.

Results from EOIM-3 thermal control materials are compared to previous Shuttle experiments, the Long Duration Exposure Facility, and ground simulations of atomic oxygen and ultraviolet radiation. Spacecraft applications of EOIM-3 results are also discussed.

EVALUATION OF AO EFFECTS ON OPTICAL THIN FILMS ON EOIM-3

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ABSTRACT

The effects of atomic oxygen (AO) and solar ultraviolet (UV) radiation on optical thin films are being studied at MSFC. Various metallic films and optical thin films were flown on STS-46 as part of the Evaluation of Oxygen Interaction with Materials Experiment (EOIM-3). This exposure of materials in Low Earth Orbit (LEO) will provide insight into the success of present ground-based simulations using thermal energy and neutral 5 eV atomic oxygen with and without simultaneous UV radiation. Comparisons to LDEF materials will also be discussed. The materials were flown in the cargo bay and exposed to the space environment, including 40 hours of direct atomic oxygen impingement. The atomic oxygen exposure was approximately 2×10^{20} atoms/cm^2.

Pure beryllium samples were flown on each of the heated trays. Silicon oxide, lithium fluoride, and magnesium fluoride coatings were deposited on beryllium blanks for passive tray samples. Optical property measurements from these samples are documented. Rutherford backscattering (RBS) measurements were also recorded.

Zerodur blanks were coated with various metallic film configurations as candidate mirror coatings for the Advanced X-ray Astrophysics Facility (AXAF). Gold, nickel, platinum, and iridium coatings with and without chrome undercoatings were made and flown on the passive trays with half-moon covers. Post-flight evaluations were made on both the exposed and unexposed halves. Coating thicknesses were either 250 Å or 750 Å metal with the chrome undercoating thickness of 100 Å. Optical property measurements including vacuum ultraviolet (VUV) reflectivity evaluations are presented. Other measurements include ellipsometry, X-ray fluorescence, and bi-directional reflectivity (BRDF) for surface roughness.

A sodium salicylate optical coating, widely used as a VUV phosphor in ground applications, was passively exposed. This sample was also flown with a half-moon cover in place to leave a control surface for post-flight analysis. Post-flight analysis included optical, ellipsometry, and BRDF measurements. Using the BRDF instrument in the transmission mode showed a definite increase in transmission through the sodium salicylate and the zerodur substrate due to exposure.

Analysis of Selected Specimens from the STS-046 Energetic Oxygen Interaction with Materials-III Experiment

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Results from the examination of lubricant, paint, silicone and butyl elastomers, composite, and thin film materials specimens flown on shuttle flight STS-046 are reported. Composite, A-276 white paint, and silvered Teflon specimens flown on the trailing edge of LDEF were reflown as part of the EOIM-3 experiment. Recession rates and optical properties are correlated with results from the Long Duration Exposure Facility and other flights. Selected silicone and butyl o-ring specimens were flown under compressive and/or tensile loads. Eight solid thin film lubricant materials were flown. An indirect scattering experiment was also flown using polyethylene "detector" surfaces concealed from direct exposure. Gold, chromic acid anodized aluminum, and silver oxide scattering surfaces were used in this experiment. The atomic oxygen exposure was predicted using the Boeing microenvironments model for direct and indirect scattering.

Boeing Defense & Space Group activities were funded by NASA Langley Research Center contract NAS1-19427, Task 8

GROUND-BASED STUDIES OF SELECTED EOIM-3 MATERIALS AND CORRELATION WITH FLIGHT DATA

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ABSTRACT

The materials, kapton, graphite, germanium, and FEP teflon, were part of various active and passive experiments on EOIM-3. These well-studied materials were also exposed to atomic oxygen in five different ground-based facilities as part of a "round robin" test. In addition, reactive and inelastic scattering experiments have been performed with a JPL atomic oxygen beam apparatus in order to study the volatile products that emerge from the surface of kapton following O-atom bombardment and the energy distribution of O-atoms that scatter from various surfaces without reaction. These controlled experiments, in many different facilities on selected materials for which high quality space data exist, can teach us a great deal about the important factors that must be controlled in a ground-based test to produce a reliable prediction of longevity in space.

The results of the round robin test and laboratory scattering experiments will be discussed and compared with EOIM-3 flight data, and conclusions will be made about the efficacy of ground-based atomic oxygen testing.

BALLISTIC MISSILE DEFENSE ORGANIZATION (BMDO) MATERIALS TESTING ABOARD THE EVALUATION OF OXYGEN INTERACTIONS WITH MATERIALS (EOIM-3) EXPERIMENT

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ABSTRACT

The NASA Evaluation of Oxygen Interactions with Materials (EOIM-3) experiment served as a testbed for a variety of materials candidates for Ballistic Missile Defense Organization (BMDO) space assets. The materials evaluated on this flight experiment were provided by BMDO contractors and technology laboratories. A parallel ground exposure evaluation was conducted using the FAST atomic oxygen simulation facility at Physical Sciences, Inc. Highlights of the results from the flight test conducted aboard STS-46 and the correlative ground exposure will be presented.

STS-46 PLASMA COMPOSITION MEASUREMENTS USING THE EOIM-3 MASS SPECTROMETER

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ABSTRACT

One of the active instruments incorporated into the Evaluation of Oxygen Interactions with Materials - 3 experiment was a quadrupole mass spectrometer. The primary objectives for this instrument, which was built by the Air Force Phillips Laboratory and was a veteran of the STS-4 flight in 1982, were to quantify the flux of atomic oxygen striking the test surfaces in the EOIM-3 payload and to detect surface reaction products from the materials in the carousel. Other speakers in this session have covered the results of these experiments.

Prior to the 40-hour-long dedicated EOIM-3 mission segment at the end of the STS-46 flight, we used the mass spectrometer to make measurements of ion and neutral gas composition in the shuttle environment. We collected about 25 hours of data during a variety of mission events, including Eureca deployment at high altitude and many tethered satellite system operations.

In this paper, we will give an overview of the pre-EOIM-3 mass spectrometer data set and will discuss several specific examples of mass spectrometer results.

POINT DEFECT FORMATION IN OPTICAL MATERIALS EXPOSED TO THE SPACE ENVIRONMENT

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ABSTRACT

Point defect formation associated with early stages of optical damage was observed unexpectedly in three different optical materials subjected to short-duration space exposure. Three calcium fluoride, two lithium fluoride, and three magnesium fluoride samples were flown on Space Shuttle flight STS-46 as part of the Evaluation of Oxygen Interactions with Materials - Third Phase experiment. One each of the calcium and magnesium fluoride samples were held at a fixed temperature of 60oC during the space exposure, while the temperatures of the other samples were allowed to vary with the ambient temperature of the shuttle cargo bay. Pre-flight and post-flight optical absorption measurements were performed on all of the samples. With one possible exception, every sample clearly showed the formation of F-centers in that section of the sample that was exposed to the low earth orbit environment. Solar vacuum ultraviolet radiation is the most probable primary cause of the defect formation; however, the resulting surface metallization may be synergistically altered by the atomic oxygen environment.

Systems

LDEF SYSTEMS SIG OVERVIEW

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ABSTRACT

The LDEF Systems SIG has been funded to accomplish the following tasks in FY94: 1) Collect and review all new LDEF systems related data generated by the various LDEF experimenters, 2) Update the April 1992 Systems SIG report with new findings including results presented at the LDEF 2nd and 3rd Symposiums and the Huntsville LDEF Materials Workshop, 3) Support the development of the LDEF Database and Archival effort, and 4) Identify specific concerns from spacecraft programs such as Hubble, SSF, AXAF, and EOS and address these concerns with LDEF data. This presentation will discuss the details of these four tasks.

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SYSTEMS RESULTS FROM FRECOPA

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ABSTRACT

The **FR**ench **CO**operative **PA**yload was positioned on the trailing edge of LDEF in position B3. It consisted of 11 experiments mounted in 3 boxes. Investigation of the wide variety of materials in the experiments (Al, Cu, W, glass, Kapton, thermal control paints, thermal blankets) and of the mounting frame and mechanisms have provided an interesting record of the material degradations possible in an LEO environment.

This paper summarises the most significant findings from these investigations, including damage produced by particle impact, atomic oxygen fluence, UV radiation and thermal cycling. One of the most important results from LDEF has been the recognition of the damage potential of the combination or 'synergy' of the above effects. The FRECOPA results improve the understanding of these effects not only for simple homogeneous targets, such as aluminium, but also for complex heterogeneous materials such as the MLI and tefloned glass thermal blankets.

This work welcomes in a new era in spacecraft material research; with the results from LDEF we can pass from the fundamental to the applied, from 2D plate damage to 3D structure damage and from individual damage mechanisms to their synergistic effects. Directions for research in these areas are proposed. In particular, the need for consideration of synergy in future ground test programmes is underlined. The validity of the LDEF results as applied to other orbits of interest for space missions is considered. This programme of work attempts to answer the appeal voiced by many spacecraft engineers for direct applications of LDEF research.

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Evaluation of Solar Cells Flown on LDEF

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A total of nine Long Duration Exposure Facility (LDEF) experiments contained solar cells, solar cell materials, and/or solar array materials. Approximately 350 solar cells were flown on LDEF and a majority of these were actively monitored during the first 325 days of the 69 month mission. In addition, several experiments evaluated cell coverglass materials and thicknesses, cell coverglass adhesives, and antireflection coatings. This paper discusses (1) the results of the numerous post-flight investigations conducted by the various experimenters and (2) lessons learned from the analysis of the data. Initial results show that cells protected by coverglasses exhibited only minor changes in electrical characteristics and that the most significant performance losses were caused by micrometeoroid and space debris.

Boeing Defense & Space Group activities were funded by NASA Langley Research Center contract NAS1-19427, Task 8

APEX AND MSFC SAMPLE-A0171 COVERSLIDE MAGNESIUM FLUORIDE DEGRADATION AND APEX FLIGHT DATA

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ABSTRACT

The Marshall Space Flight Center (MSFC) Solar Array Materials Passive LDEF Experiment (SAMPLE-A0171) and the Advanced Photovoltaic Experiment (APEX-S0014) were flown in different locations with respect to the RAM direction of the Long Duration Exposure Facility (LDEF). Results from the investigation of Atomic Oxygen interaction with the Magnesium Fluoride coating on solar cell coverslides from these two experiments will be presented as well as solar cell performance data for APEX that was recorded during the first year of the LDEF mission.

A FINAL LOOK AT LDEF ELECTRO-OPTIC SYSTEMS COMPONENTS

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Post recovery characteristics of LDEF electro-optic components from the GTRI tray are compared with their prelaunch characteristics with the characteristics of similar components from related experiments. Components considered here include lasers, light-emitting diodes, semiconducting radiation detectors and arrays, optical substrates, filters, and mirrors, and specialized coatings. Our understanding of the physical effects resulting from low earth orbit will be described, and guidelines and recommendations for component and materials choices will be presented.

EFFECTS OF THE LDEF ORBITAL ENVIRONMENT ON THE REFLECTANCE OF OPTICAL MIRROR MATERIALS

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ABSTRACT

Specimens of eight different optical mirror materials were flown in low earth orbit as part of the Long Duration Exposure Facility (LDEF) manifest to determine their ability to withstand exposure to the residual atomic oxygen and other environmental effects at those altitudes. Optical thin films of aluminum, gold, iridium, osmium, platinum, magnesium fluoride-overcoated aluminum and reactively deposited, silicon monoxide-protected aluminum, all of which were vacuum deposited on polished fused silica substrates, were included as part of Experiment S0010, Exposure of Spacecraft Coatings. Two specimens of polished, chemical vapor deposited (CVD) silicon carbide were installed in sites available in Experiment A0114, Interaction of Atomic Oxygen with Solid Surfaces at Orbital Altitudes, which included trays in two of the spacecraft bays, one on the leading edge and the other on the trailing edge. One of the silicon carbide samples was located in each of these trays.

This paper will compare specular reflectance data from the preflight and postflight measurements made on each of these samples and attempt to explain the changes in light of the specific environments to which the experiments were exposed.

EXPERIMENT NOS. S0010, A0114

EFFECTS OF LOW EARTH ORBIT ON THE OPTICAL PERFORMANCE OF MULTILAYER ENHANCED HIGH REFLECTANCE MIRRORS

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ABSTRACT

Two mirror designs developed for space applications were flown along with a standard mid-IR design on the leading and trailing edges of LDEF. Preliminary observations of induced changes in optical performance and impact related microstructural and microchemical effects are described in the proceedings of the First LDEF Retrieval Symposium[1].

In this paper, effects of the induced environment and meteoroid/debris impacts on mirror performance are described in more detail.

Scanning SIMS techniques provided mass resolved images of impact sites and dendrites and verified the earlier conclusion[1] that secondary impacts are the source of contamination associated with dendrites found on ZnS coated test samples. Microstructural surface and subsurface effects associated with high velocity (or hypervelocity) impacts on coatings were imaged with optical and scanning electron microscopy. Scanning Auger analysis provided chemical mapping of selected sites.

Analysis of reflectance spectra using the results of Auger and SIMS profiling measurements are used to identify an optical degradation mechanism. This and the impact data suggest design and fabrication modifications for obtaining improved mirror performance.

1. "Space Environmental Effects on Coated Optics", T. Donovan, J. Bennett, R. Dalbey, D. Burge and S. Gyetvay, NASA Conference publication 3134, 1361-1375 (1992).

EFFECTS OF LONG TERM SPACE ENVIRONMENT EXPOSURE ON OPTICAL SUBSTRATES AND COATINGS (S0050-2)

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ABSTRACT

The experiment consisted of Fused Silica and Ultra Low Expansion (ULE (tm)) glass samples which were either uncoated or had high reflectance silver, antireflectance, or solar rejection coatings. At the previous symposium we presented the spectral curves for the glass and coatings which defined their pre-flight, post-flight, and post-cleaning performance. Data was complete for all the samples except the fused silica substrate with an antireflection (SiO_2/TiO_2) coating, which at that time we had been unable to clean. Our final efforts at cleaning the sample and the test results will be presented.

LONG DURATION EXPOSURE FACILITY (LDEF) SPACE OPTICS HANDBOOK

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ABSTRACT

The overall objective of this effort is to construct a top-level space optics handbook that provides design guidelines based upon data collected from the Long Duration Exposure Facility (LDEF) experiment. The content of the handbook would cover optical coatings, surfaces, fiber optics, and fabricating process for lenses, windows and mirrors that were used on LDEF. The goal of this program (and handbook) is to ensure that the space community can derive the maximum benefit from the LDEF experiment relative to future optics designs for space applications. The summary of this handbook is "What did we learn from the LDEF experiment?"

This presentation will show the progress in the handbook, in the form of a draft, before it is published for distribution.

Life Science

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CONTINUED RESULTS OF THE SEEDS IN SPACE EXPERIMENT

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The results from the second generation trialing of the Seeds in Space Experiment will be presented. Progeny seed from the first generation was collected and was used to study the performance of the second generation plants.

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GERMINATION, GROWTH RATES, AND ELECTRON MICROSCOPIC ANALYSIS OF TOMATO SEEDS FLOWN ON THE LDEF

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ABSTRACT

The tomato seeds were flown in orbit aboard the Long Duration Exposure (LDEF) for nearly six years. During this time, the tomato seeds received an abundant exposure to cosmic radiation. Upon the return of the LDEF to earth, the seeds were distributed throughout the United States and 30 foriegn countries for analysis. The purpose of the experiment was to determine the long term effects of cosmic rays on living tissue. Our university analysis included germination and growth rates as well as scanning electron microscopy and x-ray analysis of the control as well as space-exposed tomato seeds.

In analyzing the seeds under the electron microscope, usual observations were performed on the nutritional and epidermic layers of the seed. These layers appeared to be more porous in the space-exposed seeds than in the Earth-based control seeds. This unusual characteristic may explain the increase in the space seeds' growth pattern. (Several test results show that the space-exposed seeds germinate sooner than the Earth-based seeds. Also, the space-exposed seeds are growing at a faster rate). The porous nutritional region may allow the seeds to receive necessary nutrients and liquids more readily, thus enabling the plant to grow at a much faster rate.

Roots, leaves, and stems were cut into small sections and mounted. After sputter coating the specimens with Argon gas, they were ready to be viewed under the electron microscope. While the specimens were under the electron microscope, several photographs were taken. The x-ray analysis displayed possible identifications of calcium, potassium, chlorine, copper, aluminum, silicon, phosphate, carbon, and sometimes sulfur and iron. The highest concentrations were shown in potassium and calcium. The space-exposed specimens displayed high concentrations of potassium, calcium, and chloride, whereas the Earth-based specimens displayed high concentrations of potassium, copper, and chloride. Therefore, there is a distinct difference in the concentration of copper and calcium in the two specimens. There were significantly high concentrations of copper in the Earth-based specimens, whereas there was no copper in the space-exposed specimens.

Future Activities

THE IMPORTANCE OF THE SPACE ENVIRONMENTS AND EFFECTS PROGRAM

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ABSTRACT

The majority of NASA's business, either directly or indirectly, involves operations in space. Space transportation with the Shuttle and expendable launch vehicles, the development of the space station, the missions to planet Earth, and the missions from planet Earth are but a few examples. To effectively conduct these businesses we must understand the environments we encounter in space, we must understand the effects that prolonged exposure in these environments will have on our spacecraft, and we must also understand the effects our space operations will have on the space environments.

In today's terrestrial environment of shrinking budgets, we must stretch our creativity and resourcefulness to develop the required understanding of the space environments and effects and to transfer this knowledge to those who need it to implement the world's space businesses. This is precisely the object of the NASA Space Environments and Effects Program (SEE Program). This paper will discuss the needs for the SEE Program and the benefits expected from it.

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FROM LDEF TO A SPACE ENVIRONMENTS AND EFFECTS PROGRAM: A NATURAL PROGESSION

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ABSTRACT

Although the LDEF data analysis is winding down, it has provided the benchmark and the initial structure for a space environments and effects (SE&E) program. Results from LDEF data analyses and investigations now form the basis of a critically-needed SE&E archive and data base system. In addition, an agency-wide effort is required to capture all elements of an SE&E program to provide a more comprehensive and focused approach to understanding the space environment, determine the best techniques for both flight and ground-based experimentation, update the models which predict both the environments and those effects on spacecraft, and, finally, ensuring that this large volume of information is properly catalogued and maintained in a form that is valuable to the end user.

Many components of an SE&E program already exist at institutions and laboratories to fulfill specific research and technical requirements. The primary purpose of this program is to take advantage of the existing pieces by coordinating and unifying the SE&E efforts. The SE&E program will support the efforts of well-established technical communities, wherein the bulk of the work will continue to be done.

A description of the requirements and justification for the SE&E program, the working structure, the implementation plan, and the goals and objectives of the SE&E program will be presented.

THE BMDO SPACE ENVIRONMENTAL EFFECTS PROGRAM

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ABSTRACT

The Ballistic Missile Defense Organization (BMDO, formerly the Strategic Defense Initiative Organization) Space Environmental Effects (SEE) program identifies, quantifies, and helps resolve issues of the effects of the space environment on BMDO space element components. The BMDO systems under consideration for providing ballistic missile defense include constellations of small satellites in the lower altitudes of the Van Allen radiation belts in middle earth orbit (MEO), and in the atomic oxygen rich low earth orbit (LEO). Both the MEO and LEO regimes have environments that can severely degrade the performance of satellite components. An important part of the SEE program approach is that the executing agent for the program, the Jet Propulsion Laboratory (JPL), works closely with the BMDO contractors to identify and address uncertainties in the application of new thermal control, optical, structural, and electronic materials and technologies in the space environment. This approach ensures a focused program, which is crucial in a severely constrained budget environment. The program conducts short duration accelerated effects space tests from the Shuttle and long duration mission-like space tests to quantify the space effects provided by the BMDO contractors. Identical samples are also exposed to well controlled simulated environments in ground test chambers. Results from space and ground tests are then correlated to develop low cost ground test procedures for reliable prediction of performance in space. The conference presentation will describe in more detail the philosophy and past successes of the program. The three long term flights with more than ten space effects related payloads that are planned will be described, as will two Shuttle-based sample trays. The results from the unique atomic oxygen and radiation effects ground chambers that have been developed will also be described.

LDEF ARCHIVAL SYSTEM

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ABSTRACT

The LDEF archival system currently under development will serve as a long term resource for LDEF information and the basis for a broader space environment and effects archive system. The central core of this system is an electronically-accessible directory and information system that will identify all resources in the archive, including the LDEF project / mission documentation, hardware, data, analysis, photographs and publications. The directory will also provide electronically-stored data and information, and instructions to obtain archive elements not electronically available. The general scope of the LDEF archival system was presented at the Second LDEF Post-Retrieval Symposium in 1992. In this paper, the status of the LDEF archival system development will be presented along with further details of its structure. A discussion of directory and archive locations, access, policy and procedures will be included. Some elements of the LDEF archival system have been developed and are accessible through computer networks, personal computer software and non-electronic methods. This archive system is of critical value to NASA's capability to understand the space environment and to design spacecraft to most effectively perform missions in space without unanticipated consequences of radiation, molecular contamination and atomic species, meteoroids, debris and other aspects of the space environment.

LONG DURATION EXPOSURE FACILITY (LDEF) ANNOTATED BIBLIOGRAPHY

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As part of the effort to archive the LDEF data analysis, an LDEF annotated bibliography has been compiled. This bibliography will eventually be available electronically, as well as in hardcopy. The electronic system will be capable of periodic updates. The compilation of LDEF papers can be updated, and converted to a Space Environments and Effects (SEE) compilation by integrating the results of other SEE research. The hardcopy database will be divided into categories similar to the LDEF Symposia: Induced Environments and Natural Environments (i.e. Radiation, Meteoroid and Debris, Microgravity) and Space Environment Effects. The "Effects" categories will be divided into Materials, Systems, and Life Science. Within the "Effects" category, further breakdowns will developed, i.e., materials: polymers, metals, paints/coatings. Each entry (both on the hard copy and the electronic database) will contain the author(s) name, affiliation(s), title of the paper, journal or report name, date, and an abstract. All papers in the open literature will be included: conference papers, journal articles (foreign and domestic), and unrestricted contractor reports. The following is an example of an entry in the annotated bibliography:

MESHISHNEK, M. J.; GYETVAY, S. R.; JAGGERS, C. H. (Aerospace Corp., El Segundo, CA.) " Long Duration Exposure Facility Experiment M0003 Deintegration/Findings and Impacts" 1991; In NASA Langley Research Center, LDEF 69 Months in Space. First Post-Retrieval Symposium, NASA-CP-3134, Part 2, p 1073-1107.

The Long Duration Exposure Facility (LDEF) Experiment M0003 consists of 19 subexperiments from laboratories and contractor organizations and was designed to study the effects of the space environment on a large variety of spacecraft materials and components, both current and developmental. The experiment was housed in four LDEF trays and contained over 1250 specimens, two data systems, and two environment exposure control canisters. Nearly identical pairs of trays were located on the leading and trailing edges of LDEF. The materials in these trays span nearly all generic functions in spacecraft such as optics, thermal control, composites, solar power, and electronics. Effects of the space environment, such as vacuum, ultraviolet, atomic oxygen, meteoroids and debris, thermal cycling, and synergistic effects on various samples, are described. Summaries of the on-board data are presented. (Author)

LDEF'S CONTRIBUTION TO THE DESIGN OF THE SPACE STATION

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ABSTRACT

The design of the Space Station presented new challenges in the selection and qualification of materials that would survive in low earth orbit for a duration up to 30 years. All previous experience was for life-limited Satellites usually less than five years. In addition, the only behavioral materials data in space was based on temperature measurements and telemetry data. For many of the flight experiments it was difficult to distinguish between changes due to contamination and that occurring from degradation of the surface optical properties due to environmental effects. Ground testing had not evaluated the synergistic effects from UV and AO and in many cases no AO data was available. There was no established design data base for the design development of the Space Station. Then came LDEF. The earliest data from LDEF was obtained prior to public release in order to help make better design decisions. As the data continued to be released, reverification of early decisions were confirmed or in a few cases modified based on the more mature data. Many specific examples are available related to thermal control coatings, contamination deposition, MLI, lubricants to name a few. Just recently reviews were initiated to better understand the many different effects from silicone contamination and ways to detect ground contamination prior to launch.

SPACE STATION PROGRAM STATUS AND RESEARCH CAPABILITIES

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ABSTRACT

Space Station will be a permanent orbiting laboratory in space which will provide researchers with unprecedented opportunities for access to the space environment. Space Station is designed to provide essential resources of volume, crew, power, data handling and communications to accommodate experiments for long-duration studies in technology, materials and the life sciences. Materials and coatings exposure research will be supported by Space Station, providing new knowledge for application in Earth-based technology and future space missions.

Space Station has been redesigned at the direction of the President. The redesign was performed to significantly reduce development, operations and utilization costs while achieving many of the original goals for long duration scientific research.

An overview of the Space Station Program and capabilities for research following redesign will be presented. Accommodations for pressurized and external payloads will be described. Plans for research and current program status will be summarized.

SPACE STATION AS A LONG DURATION EXPOSURE FACILITY

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ABSTRACT

There is need for a space platform for experiments investigating long duration exposure to space. This platform should be maintainable in the event of a malfunction, and experiments should be easily recoverable for analysis on Earth. The US Space Station Freedom provides such a platform.

The current Space Station configuration has four external experiment attachment sites, providing utilities and data support, distributed along the external truss. There are also other sites that could potentially support long duration exposure experiments. This paper describes the resources provided to payloads at these sites, and cites examples of integration of proposed long duration exposure experiments on these sites. The environments to which external attached payloads will be exposed are summarized.

A MATERIALS EXPOSURE FACILITY

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Abstract

The NASA Langley Research Center has developed a proposal for a Materials Exposure Facility (MEF) as an external attached payload for Space Station Freedom. The objective of the facility is to provide a test bed in space for conducting long-term (> 1 year) flight exposure experiments in the low Earth orbital space environment of Space Station Freedom. The facility will provide 28 experiment trays, 1 m x 1 m, similar to the Long Duration Exposure Facility (LDEF) trays. Each tray location will have a power and data interface and provisions for robotic installation and removal. Space environmental monitoring for each side of the Ram, Port, Wake, Starboard, and Nadir exposure directions will be provided using a modified SAMMES flight package. The MEF is designed for robotic installation on Freedom and to be operational for the lifetime of Space Station Freedom.

This Materials Exposure Facility is intended to complement other flight experiments on free-flyers like the proposed LDEF II. The easy access provided by Space Station Freedom will expedite the periodic removal of experiments and replacement with new experiments. Although Freedom is being redesigned, an unobstructed external payload attachment site suitable for this experiment is in the new design requirements.

AN LDEF FOLLOW-ON SPACECRAFT CONCEPT

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ABSTRACT

The successful flight, retrieval, and analyses of the Long Duration Exposure Facility (LDEF) experiments has demonstrated the value of long duration space exposure for a broad spectrum of science and engineering investigations. The original LDEF was an excellent gravity gradient spacecraft, but because of its 9 m length and 9,700 kg mass it was difficult to manifest on the Shuttle, for either launch or retrieval, in conjunction with other payloads.

This paper discusses an LDEF follow-on spacecraft concept whose short stowed length (~3 m) greatly improves Shuttle manifesting opportunities while still providing very large surface area exposure for experiments. Deployable 'wings' on each end of the short, 'cylindrical' main body of this new spacecraft provide the means for gravity gradient stabilization while greatly increasing the spacecraft surface area. The center section of the spacecraft is oriented with the end faces of the twelve sided, 4.2 m diameter 'cylinder' perpendicular to the velocity vector thus providing large areas for experiments in both the ram and anti-ram directions as well as additional exposure area around the periphery of the cylinder. When deployed and properly oriented with the Shuttle's Remote Manipulator System (RMS), both wings of the spacecraft are oriented edge on to the direction of motion and lie in the plane which contains the local gravity vector. The relatively thin wings readily accommodate dual side exposure of glass plate stacks for cosmic ray detection. Flat surfaces mounted normal to and on the periphery of the wings provide additional areas in both the ram and anti-ram directions for cosmic dust, micrometeoroid, and orbital debris collection free of contamination from 'splatter' off secondary surfaces. The baseline concept provides enhancements not available on the original LDEF such as solar array generated electrical power and data telemetry.

Status of the efforts to promote support for and ultimately space flight of this concept will be presented. Suggestions for improvements in the spacecraft design and proposed utilization are solicited.

SPACE ENVIRONMENT AND EFFECTS EXPERIMENTS ABOARD THE SPACE TECHNOLOGY RESEARCH VEHICLE-1 (STRV-1) MISSION

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ABSTRACT

STRV-1 is a mission developed by the United Kingdom's Defense Research Agency (DRA) consisting of two satellites (1a & 1b) to be launched into a geosynchronous transfer orbit by an Ariane 4 in early 1994. BMDO is collaborating with the DRA to fly four experiments on the 1b satellite. These four experiments have been developed by the Jet Propulsion Laboratory and include a cooler vibration suppression demonstration and three radiation experiments. In this presentation we will discuss the radiation effects experiments which include the demonstration of a miniature SEU and total dose radiation monitor (RADMON), the evaluation of advanced LWIR detectors using heterojunction internal photoemission (HIP) sensors, and the evaluation of fault tolerant analog neural network chip. Topics to be covered include descriptions of the experiments, flight test plans, ground-based radiation testing and planned data correlation activities.

LONG DURATION EXPOSURE FACILITY POST-FLIGHT DATA AS IT INFLUENCES THE TROPICAL RAINFALL MEASURING MISSION

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ABSTRACT

The Tropical Rainfall Measuring Mission (TRMM) is a joint United States and Japan observatory program that will conduct systematic measurements of tropical rainfall required for weather and climate research. NASA's Goddard Space Flight Center in Greenbelt, Maryland will design, build, and test the observatory. TRMM is scheduled for launch in August 1997 from Tanegashima, Japan. The observatory will fly in a circular orbit having an inclination of 35 degrees and an altitude of 350 kilometers (189 Nautical miles). TRMM will be in orbit during the next period of maximum solar activity and is predicted to experience an atomic oxygen fluence of 8.9 x 10^{22} atoms per square centimeter. This fluence is ten times higher than the atomic oxygen impingement incident to the Long Duration Exposure Facility (LDEF). Because of TRMM's predicted harsh environment, most commonly flown spacecraft outer layer materials will not survive the three year mission.

This paper will provide an overview of the TRMM material concerns and subsystem design issues. It will also highlight how the LDEF post-flight data is influencing the design of TRMM and the TRMM material selection process.

ELEMENT MATERIAL EXPOSURE EXPERIMENT BY EFFU

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ABSTRACT

National Space Development Agency of Japan (NASDA) is planning to perform "Element Material Exposure Experiment" using Exposed Facility Flyer Unit (EFFU).

EFFU is installed on Space Flyer Unit (SFU) as a partial model of space station JEM exposed facility. Several experiments are proposed by five prime investigators including NASDA and IHI.

Solid lub., CFRP, optical materials, anodize coatings, beta-cloths, OSRs, paints, solar cells are to be exposed in the experiments.

SFU-EFFU is scheduled to be launched by H-II rocket in January or February of 1995, then various tests and experiments will be performed for three months on orbit of 500 km altitude, and will be retrieved by US Space Shuttle and return to the ground.

Description Of The Orbital Meteoroid And Debris Counting Experiment To Fly On The Clementine Inter-Stage Adaptor Spacecraft

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ABSTRACT

The Clementine Mission will involve two spacecraft. The primary spacecraft will initially orbit the moon, and later, it will fly-by a near Earth asteroid. The interstage adaptor for the primary spacecraft will become a secondary spacecraft in a highly elliptic Earth orbit (~167,000 km apogee) after the primary spacecraft is deployed. The Orbital Meteoroid and Debris Counting Experiment (OMDC Experiment) is one of several technology experiments that will fly on the interstage adaptor spacecraft. The objectives of the OMDC Experiment are; a) to establish the altitude variation in the population of small mass manmade debris, b) to establish the population of small mass meteoroids near Earth, c) to make a first order determination of the meteoroid and debris hazard to spacecraft employing Earth gravity assist for deep space travel, and, d) to demonstrate the performance of an ultra lighweight particle impact detector that can be used on future spacecraft to monitor the health of the spacecraft and to continue the monitoring of the manmade debris environment. The experiment will utilize improved lighter weight MOS (metal-oxide-silicon) impact detectors of the type that have been flown on several previous spacecraft.

This paper will provide a more detailed description of the OMDC Experiment and it will present predictions of the data expected from it.

PROTECTION OF MATERIALS IN THE SPACE ENVIRONMENT

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ABSTRACT

The Protection of Materials in the Space Environment project is part of a larger Canadian Space Agency program called STEAR (Strategic Technologies for Automation and Robotics). The STEAR Program was established to encourage the participation of Canadian companies, universities and research organizations in automation and robotic technologies important for the evolution of the Mobile Servicing System (MSS). Canada is responsible for the development of the MSS for Space Station Freedom.

"Protection of Materials in the Space Environment" was initiated as a supporting technology development project for automation and robotics technology. Its objective is to identify, develop and demonstrate through detailed testing and evaluation, effective means of protecting structural materials and finishes used for the MSS, which will maintain their physical and functional integrity in the Low Earth Orbit environment for 10 to 30 years. Three Protection of Materials research and development contracts have recently started and will proceed over the next three years through to proof-of-concept and prototype development.

The presentation will briefly discuss the broad aspects of the Protection of Materials in the Space Environment project including project objectives and time lines. The participating companies and their topics will also be identified.

SPACE ACTIVE MODULAR MATERIALS EXPERIMENTS (SAMMES): LOW EARTH ORBITAL MISSION ABOARD THE SPACE TEST EXPERIMENTS PLATFORM (STEP-3)

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ABSTRACT

The Ballistic Missile Defense Organization (BMDO) has developed a flight instrument, Space Active Modular Materials ExperimentS (SAMMES), for assessing the effects of the near earth orbital space environment on spacecraft materials. SAMMES consists of small test modules cabled to a system control module (SCM). The SCM provides the power, command and data interface to the host spacecraft and operates the test modules through a standard data interface (MIL-STD-1553B). Four test modules (TMs) have been designed for SAMMES: a low earth orbital (LEO) environment monitor TM, a calorimeter TM, a temperature-controlled quartz crystal microbalance/atomic oxygen actinometer TM, and a solar photovoltaicTM. The TMs employ state-of-the-art sensors including heated calorimeters, temperature-controlled quartz crystal microbalances, heated atomic oxygen actinometers, FET total radiation dose monitors, sun position sensors and solar photodiodes, any of which may be mounted remotely from the TMs. The initial flight of SAMMES will be aboard the Space Test Experiments Platform (STEP-3), sponsored by the DoD Space Test Program. STEP-3 will carry the full complement of SAMMES modules, populated with BMDO and NASA test materials and solar photovoltaics, to a 450 km circular orbit. The mission plan calls for a third quarter 1994 launch with a minimum data collection period of one year and a goal of at least three years on orbit. Thermal control materials, optical coatings and advanced solar photovoltaics will be evaluated to assist spacecraft designers in final materials selection. Subsequent missions for SAMMES are expected to occur at higher altitudes and will utilize new sensors and modules. The TMs may be capable of autonomous operation, thus eliminating the need for an SCM. In the future, SAMMES TMs could be used to provide autonomous state-of-health monitoring for a variety of spacecraft.

THE ORBITAL DEBRIS DETECTOR CONSORTIUM: SUPPLIERS OF INSTRUMENTS FOR *IN-SITU* MEASUREMENTS OF SMALL PARTICLES IN THE SPACE ENVIRONMENT

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ABSTRACT

The participants listed above have joined together to form a consortium of instrument suppliers for in-situ detection of small particles in the space environment. The participating groups offer flight proven technologies for detection and analysis of particles ranging in size from submicron to 10 cm. The detector technologies represented by these groups are: acoustic, MOS (metal-oxide-silicon) capacitor-discharge, optical scatter, plasma, and PVDF (polyvinylidene fluoride). Summary descriptions of each technology will be presented, including operational characteristics, spacecraft interface and resource (mass/power/telemetry) requirements, and cost and delivery schedules.

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This volume is a compilation of abstracts submitted to the Third Long Duration Exposure Facility (LDEF) Post-Retrieval Symposium. The abstracts represent the data analysis of the 57 experiments flown on the LDEF. The experiments include materials, coatings, thermal systems, power and propulsion, science, (cosmic ray, interstellar gas, heavy ions, micrometeoroid, etc.), electronics, optics, and life science.

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